

Search for the Higgs Boson Decaying to W^+W^- at CMS

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FNAL RA Candidate Talk
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Introduction

- The Higgs Boson is the only particle in the Standard Model not yet experimentally observed

- Provides the mechanism for electroweak symmetry breaking

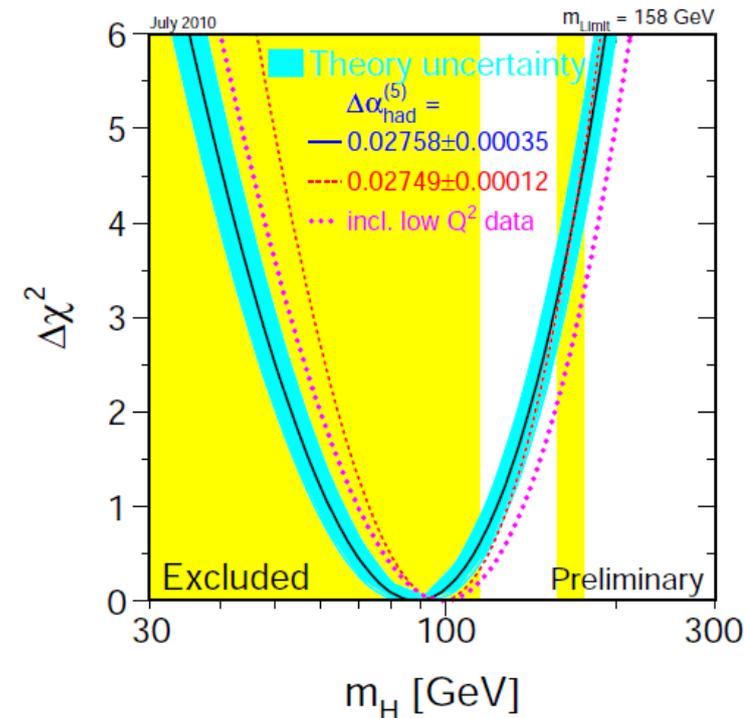


W and Z boson masses

- Generates masses of fermions
- Currently the main focus of the LHC physics program and one of the main reasons for its construction

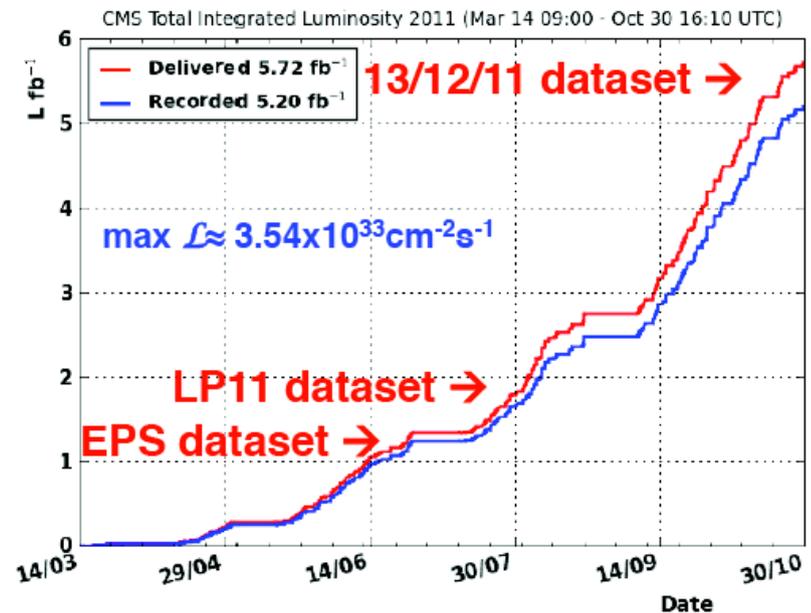
- Mass not predicted by the Standard Model

...but constrained by electroweak precision measurements and direct searches at LEP and Tevatron



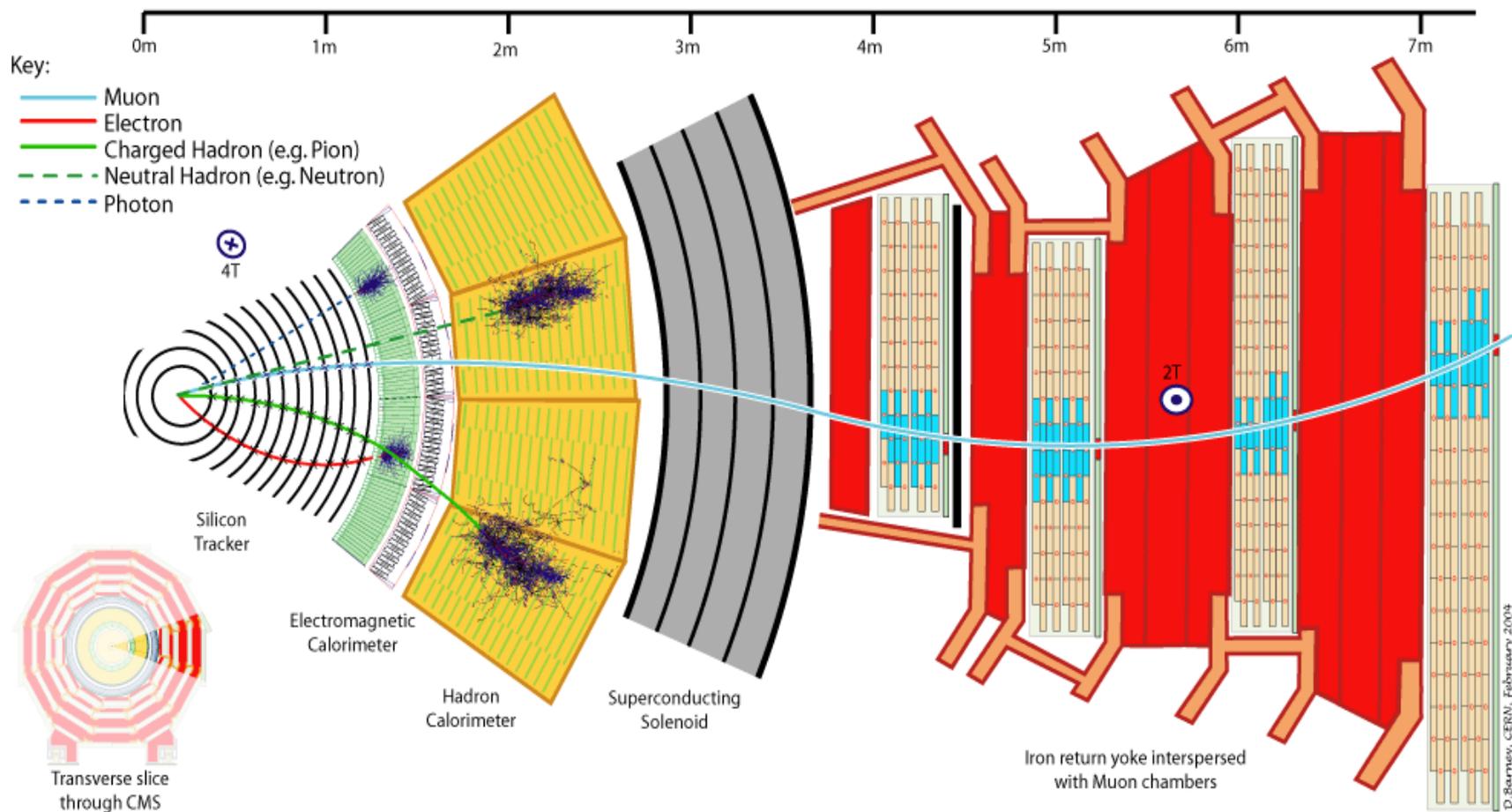
Large Hadron Collider

- Proton – Proton Collider @ center of mass energy of 7 TeV
- Extraordinary performance in 2011
 - Approaching half max design instantaneous luminosity in just 2 years of operation



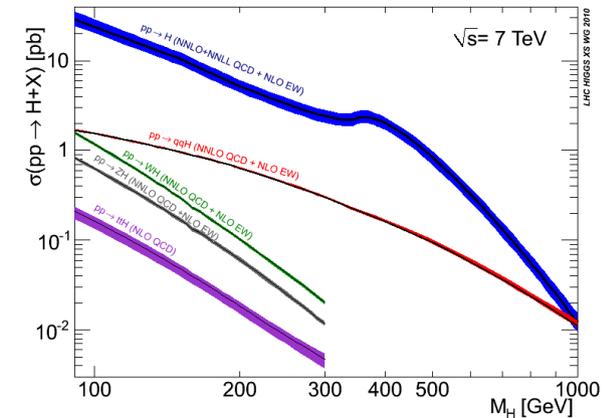
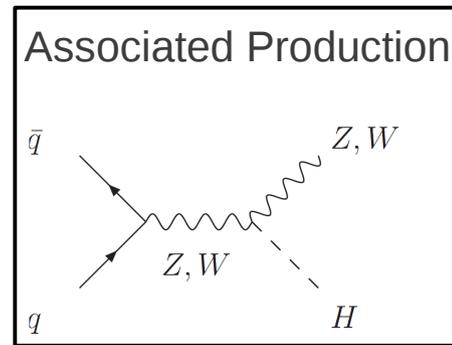
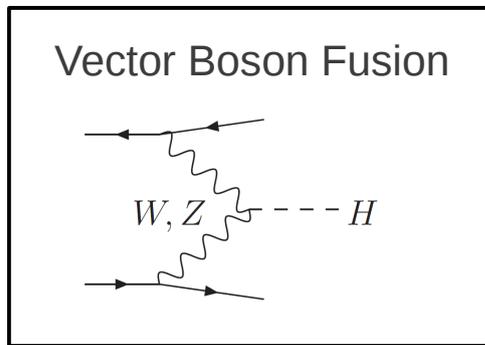
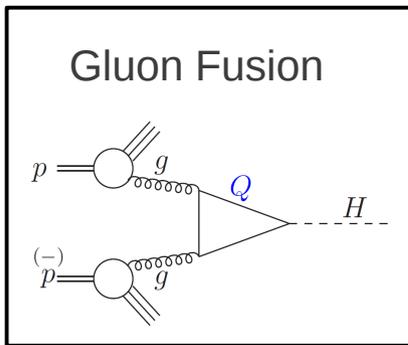


CMS Detector

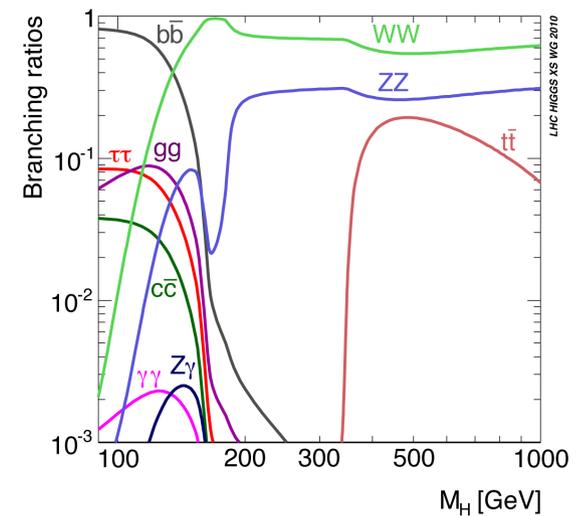


Higgs Production @ LHC

Higgs production modes at the LHC:



- Decay mode to $W+W^-$ has largest branching ratio over the majority of the Higgs mass range



Higgs \rightarrow W^+W^-

Clean experimental signature :

2 Leptons
(e or μ)

+

2 neutrinos

MET
missing transverse energy

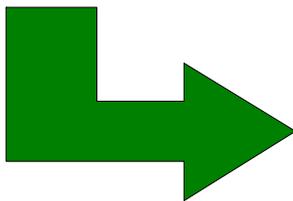
But...NO mass peak!



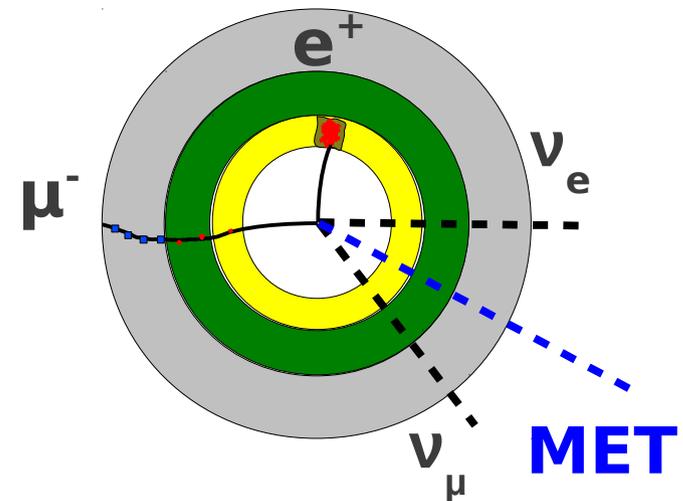
Must count events to infer a signal



Must know how much is not signal



**Analysis is all about
control of backgrounds!**





Triggers

- Triggers are crucial at a hadron collider :

Total rejection
factor $\sim 5 \times 10^4$

- Main “workhorse” triggers : Dilepton triggers (ee , $\mu\mu$, e μ)
 - **A challenge to retain leptons with pT down to 10 GeV !**
 - Achieved per lepton efficiency of
 - **~99% for electrons**
 - **~95% for muons**

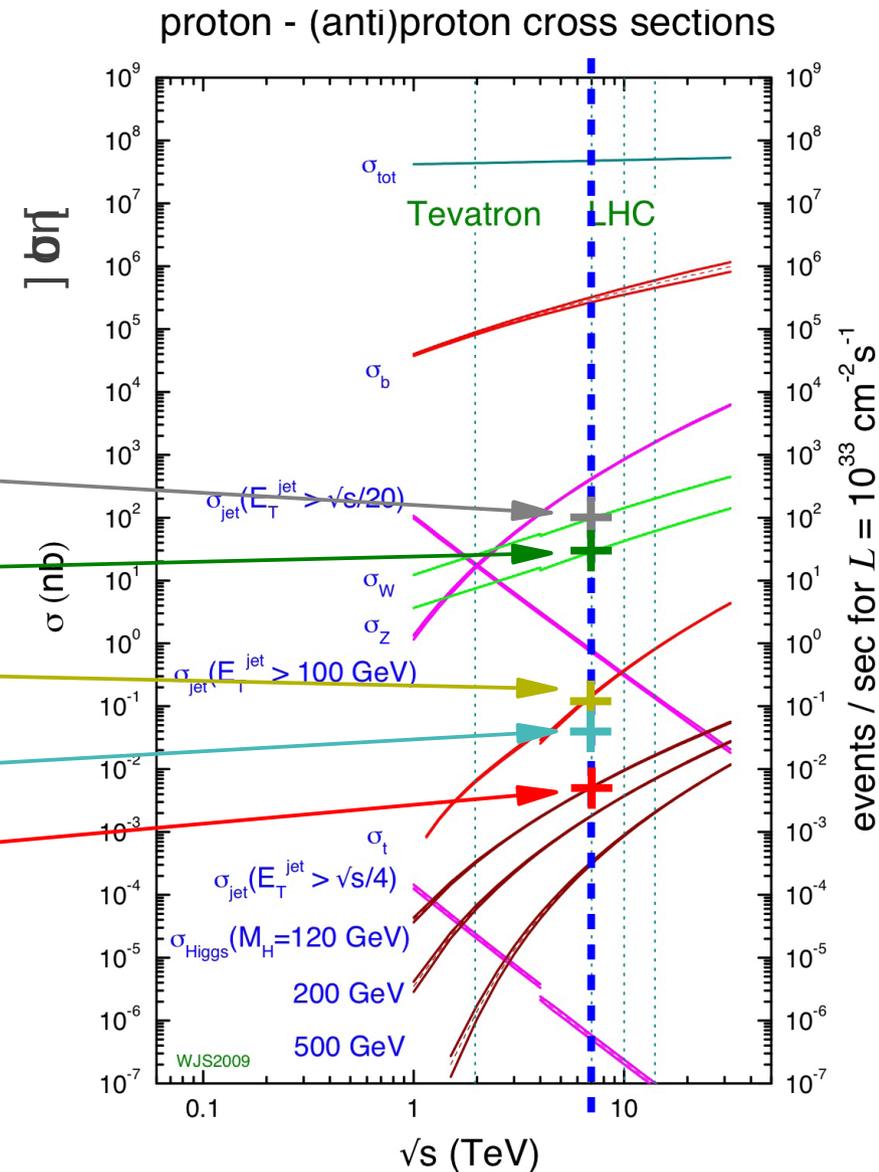
Signal triggers are not the only important triggers!

- Suite of Utility triggers for:
 - Fake lepton enhanced triggers for **control of backgrounds**
 - Z \rightarrow ll events, one unbiased leg for **measuring efficiencies**

Higgs \rightarrow W^+W^-

Analysis is all about control of backgrounds!

- Main background production cross sections up to **5 orders of magnitude** larger than signal



Analysis Strategy

Analysis done in 2 conceptual steps:

(1) WW Pre-selection

- Establish the WW signature
- Establish control on estimates of main backgrounds

(2) Higgs Selection

- Discriminate Higgs against WW background
 - Cut-Based selection
 - MVA discriminator

Analysis Strategy

Analysis done in 2 conceptual steps:

(1) WW Pre-selection



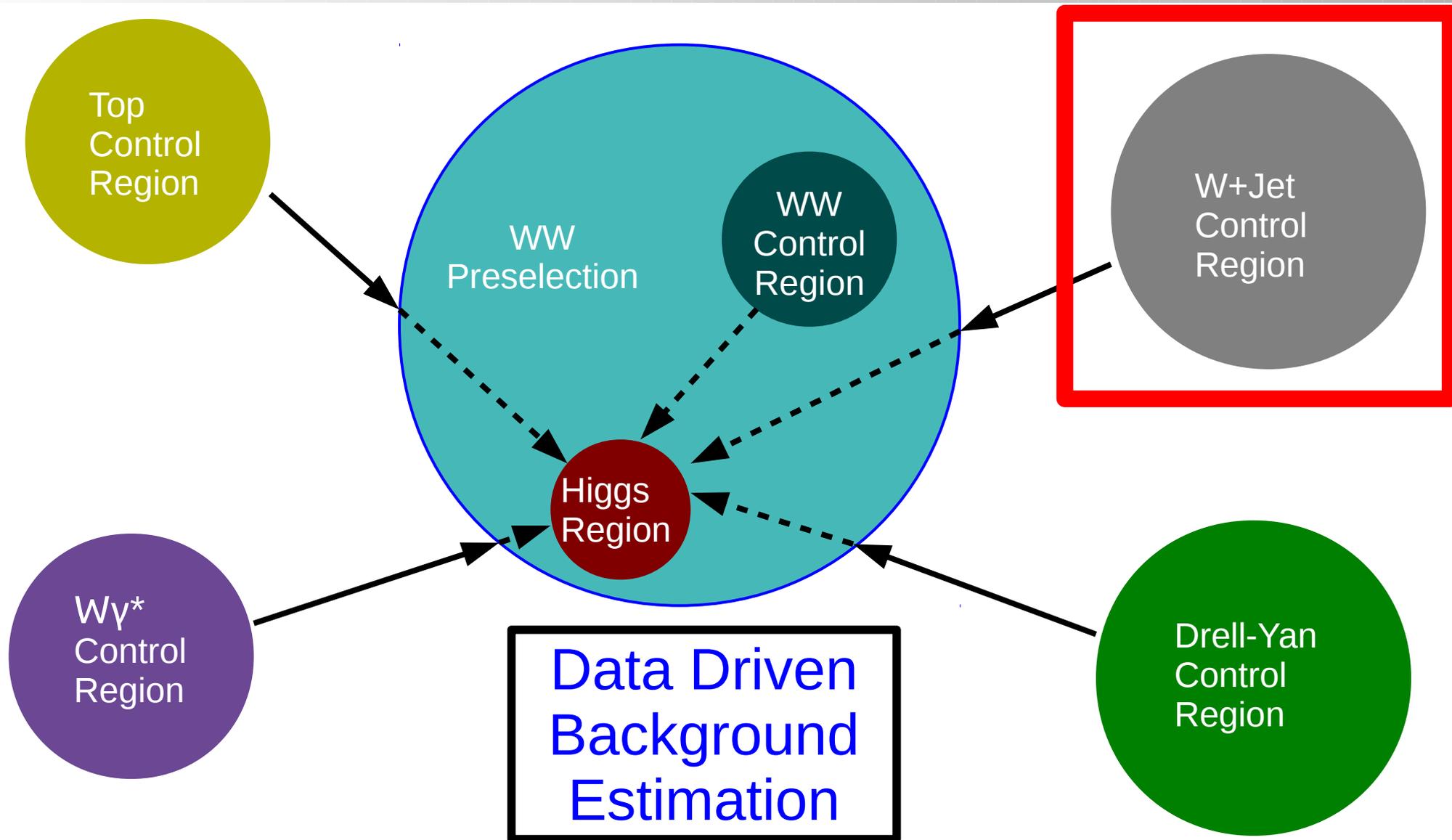
- Establish the WW signature
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(2) Higgs Selection

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Establishing Control of Backgrounds





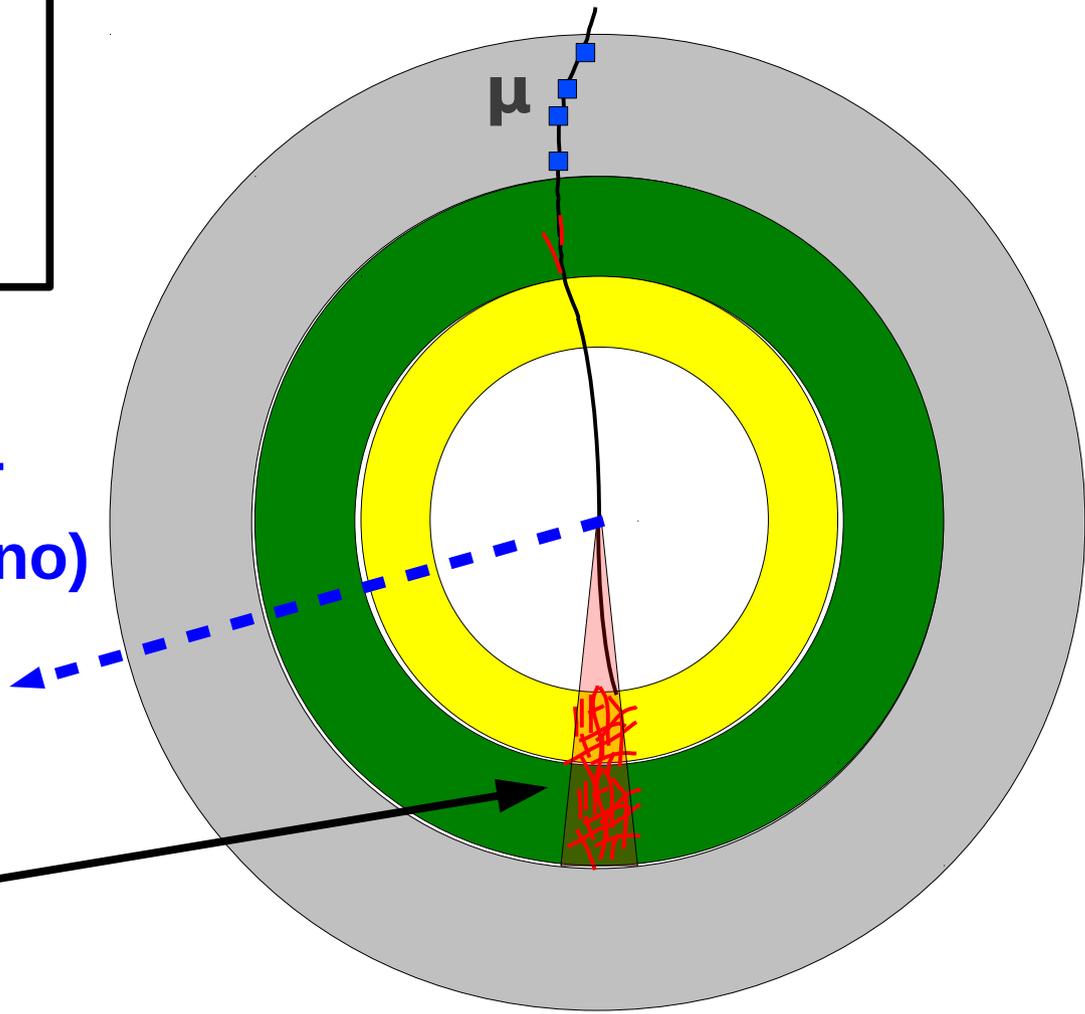
W+Jets : Fake Lepton

W+Jets cross section more than **4 orders of magnitude** larger than signal

One Real Lepton (from W boson)

MET (Neutrino)

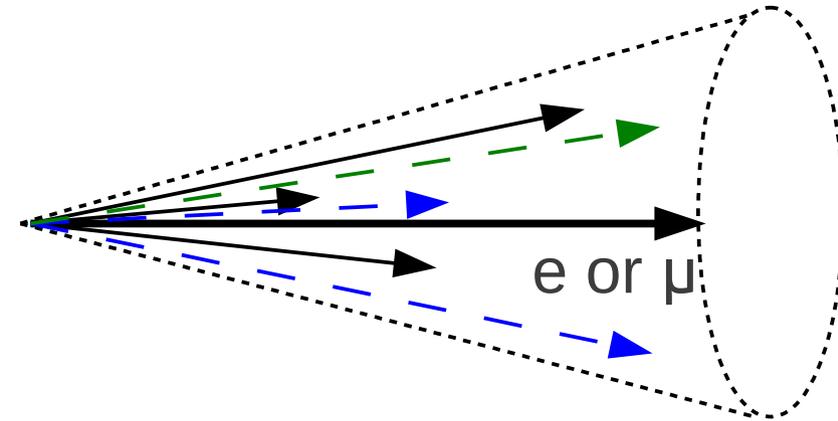
A quark or gluon that "fakes" a lepton



Primary Tool to Suppress W+Jets: Lepton Identification and Isolation

Isolation :

- No energy / momentum flow nearby
- Suppresses bulk of fragmentation



Muons :

- Requirements on:
 - Track and muon segment quality
 - Matching quality
 - Impact parameter

Electrons :

- Track to cluster matching
- Shower shape
- Impact parameter
- $\gamma \rightarrow e^+e^-$ conversion rejection

- Use of multi-variate tools are crucial :
 - **Improvement in bkg rejection of factor of 2-3**

Work is on-going
a lot of progress
since last public
results

Estimating W+Jets Background

- “Fake” leptons are very difficult to simulate with Monte Carlo
 - In the tails of distributions...
 - Dependencies on many not-so-well-known aspects such as fragmentation, detector material model, ...

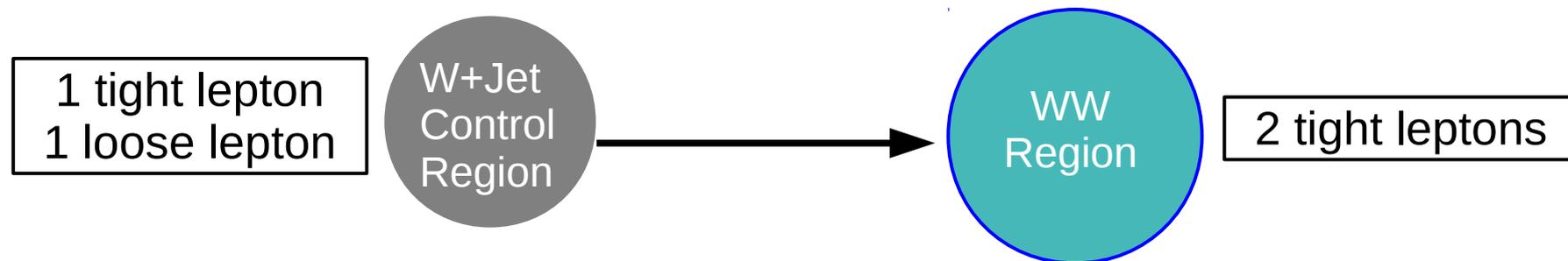


Need Data-Driven Estimate

Define a baseline loose lepton selection:

Loose ID, Isolation, & impact parameter requirements

Extrapolate in lepton selection efficiency (“fake rate”)



Estimating W+Jets Background: Measure the “Fake Rate”

$$\text{Fake Rate: } \epsilon_{\text{fake}}(p_T, \eta) = \frac{N_{\text{pass tight}}(p_T, \eta)}{N_{\text{loose}}(p_T, \eta)}$$

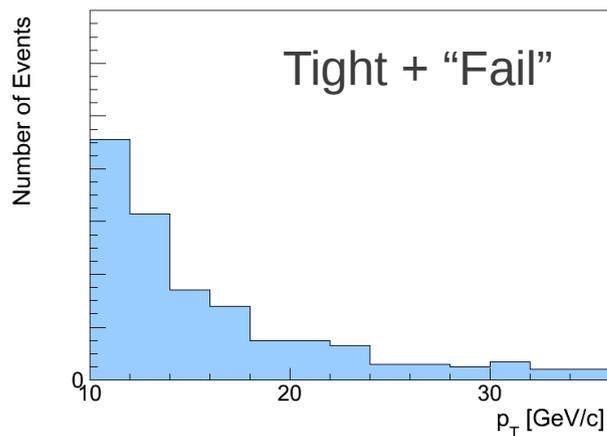
- Fake rate must be measured for background leptons (“fakes”)
 - Use single lepton + jet events enriched **in QCD multijet events**
 - Must suppress “real” leptons from W+jets
 - MET < 20 GeV, $m_T < 20 \text{ GeV}/c^2$, lepton $p_T < 35 \text{ GeV}$
 - Parameterize in lepton p_T and $|\eta|$ to account for kinematic dependencies

Estimating W+Jets Background: Extrapolation

- Select data events with 1 tight lepton + 1 “fail” lepton

“fail” = loose lepton but fails tight selection

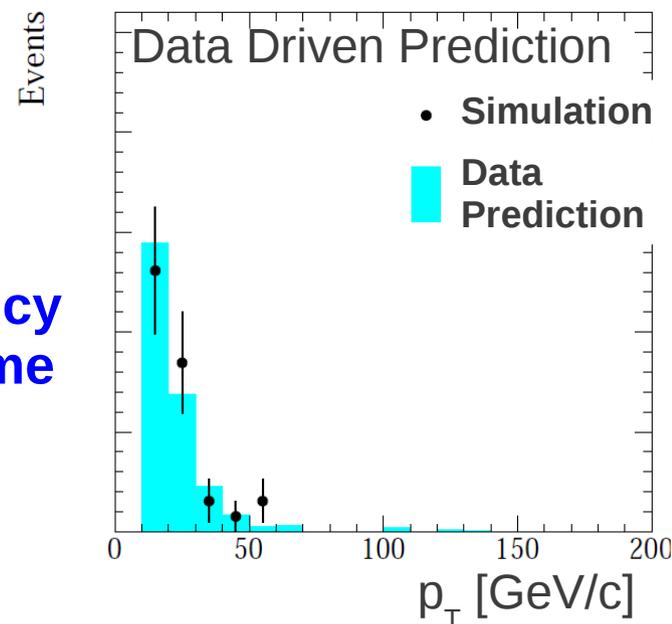
- Weight each event by :
$$w_i = \frac{\epsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)}{1 - \epsilon_{\text{fake}}(p_{\text{Ti}}, \eta_i)}$$



Critical Assumption:



Background lepton efficiency in W+Jets events is the same as in QCD multijet events



- Systematic uncertainties cover any failure of this assumption

For low mass Higgs: ~15% of total bkg

W+Jets : Systematics

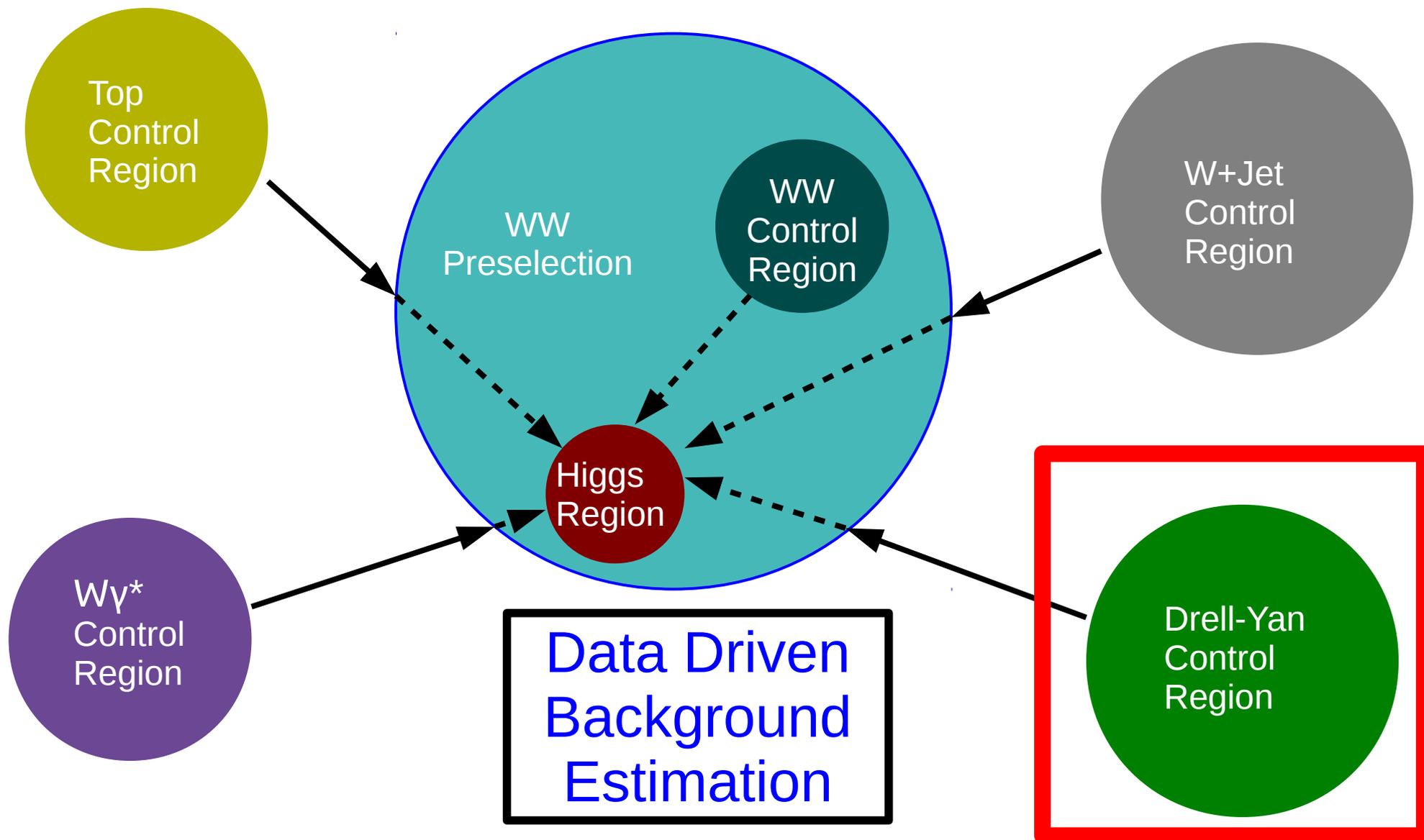
- **Systematic Uncertainties : fake rate sample dependence**
 - QCD → W+Jets extrapolation
 - Fake lepton (parton / jet) spectrum uncertainty

One of the leading uncertainties in the analysis with increasing luminosity

- **More Cross Checks**
 - Control region: Higgs signal phase space but **two same charge leptons**
 - Enhanced in fake lepton background
 - Further check of predicted background vs observed data



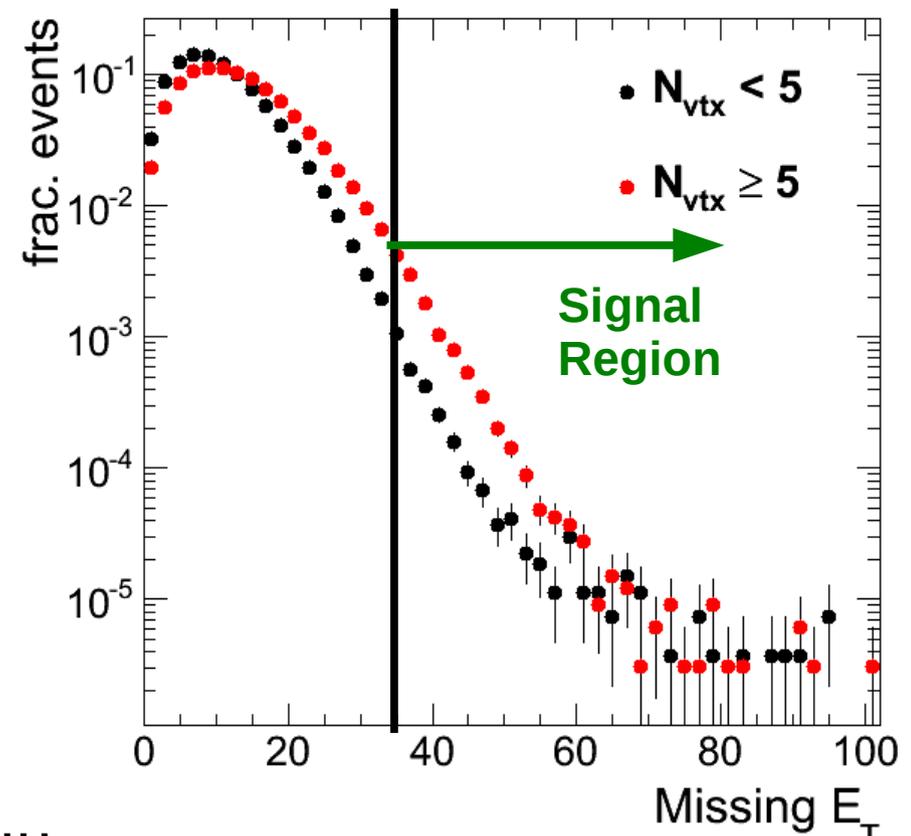
Establishing Control of Backgrounds



Drell-Yan $\rightarrow ee / \mu\mu$: Fake MET

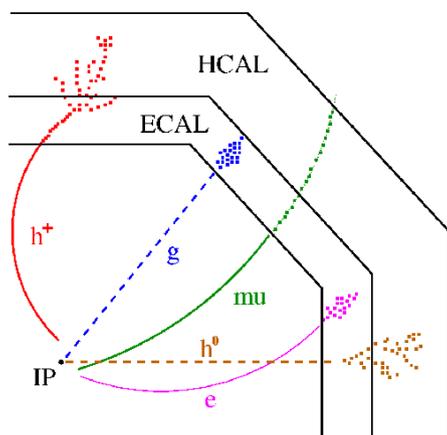
Drell-Yan cross section
more than **3 orders of magnitude** larger than
signal

- Calorimeter energy measurement uncertainty creates a tail of instrumental “fake” MET
- Pileup has a huge **detrimental** effect on MET resolution
- Categorize events into $e\mu$ and $ee/\mu\mu$

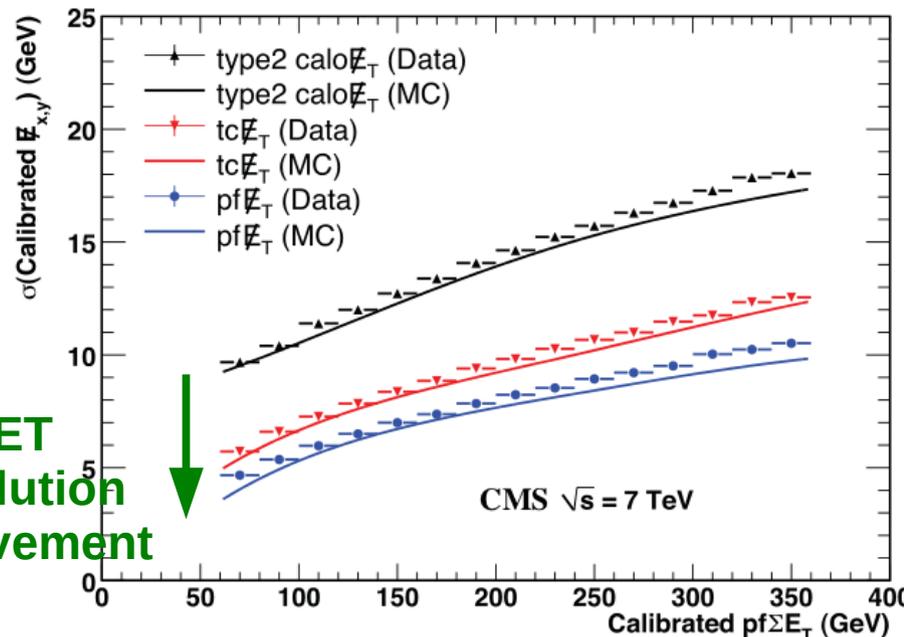
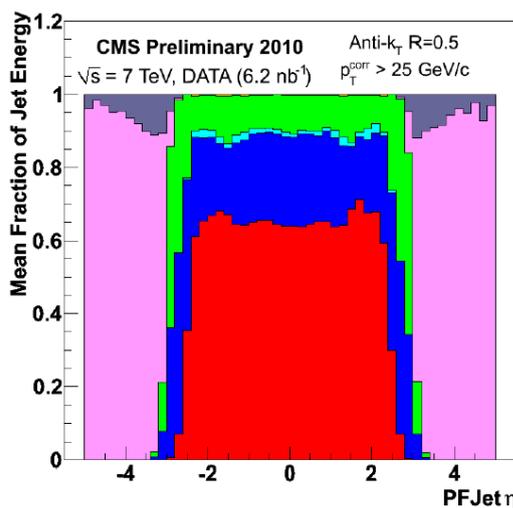


Particle Flow

CMS tracker angular resolution & ECAL segmentation allows track-cluster matching \Rightarrow **Pseudo-Full Event (Particle) Reconstruction**

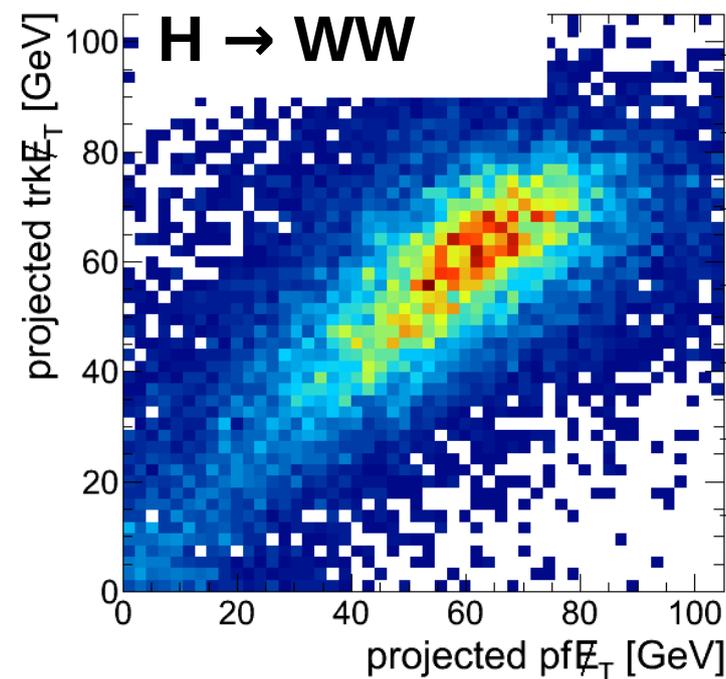
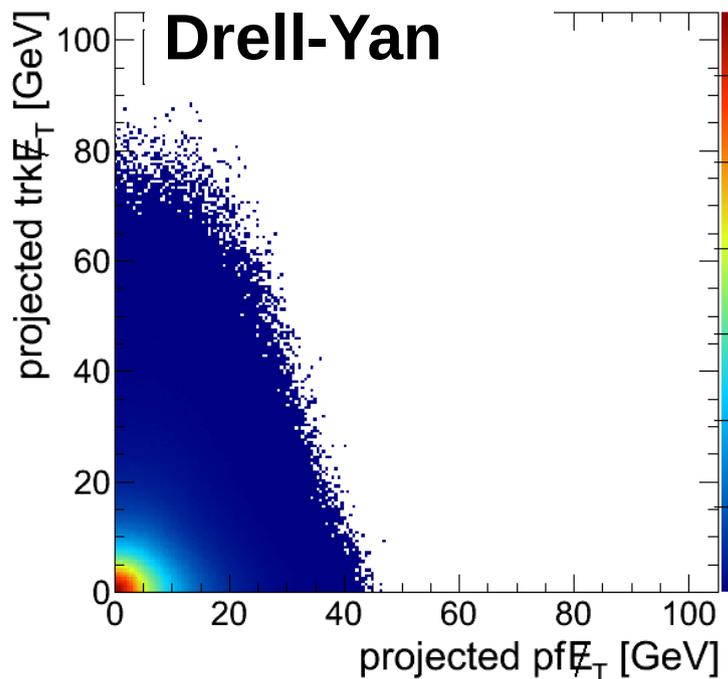


Significant improvement to (missing) energy resolution by combining tracking and calorimeter information



Track MET

- Charged particles can be associated with the event primary vertex
 - Can build MET from charged particles only → “Track MET”
- Some performance gained using **Min (PF MET , Track MET)**
 - Exploits differences in correlations for signal and background

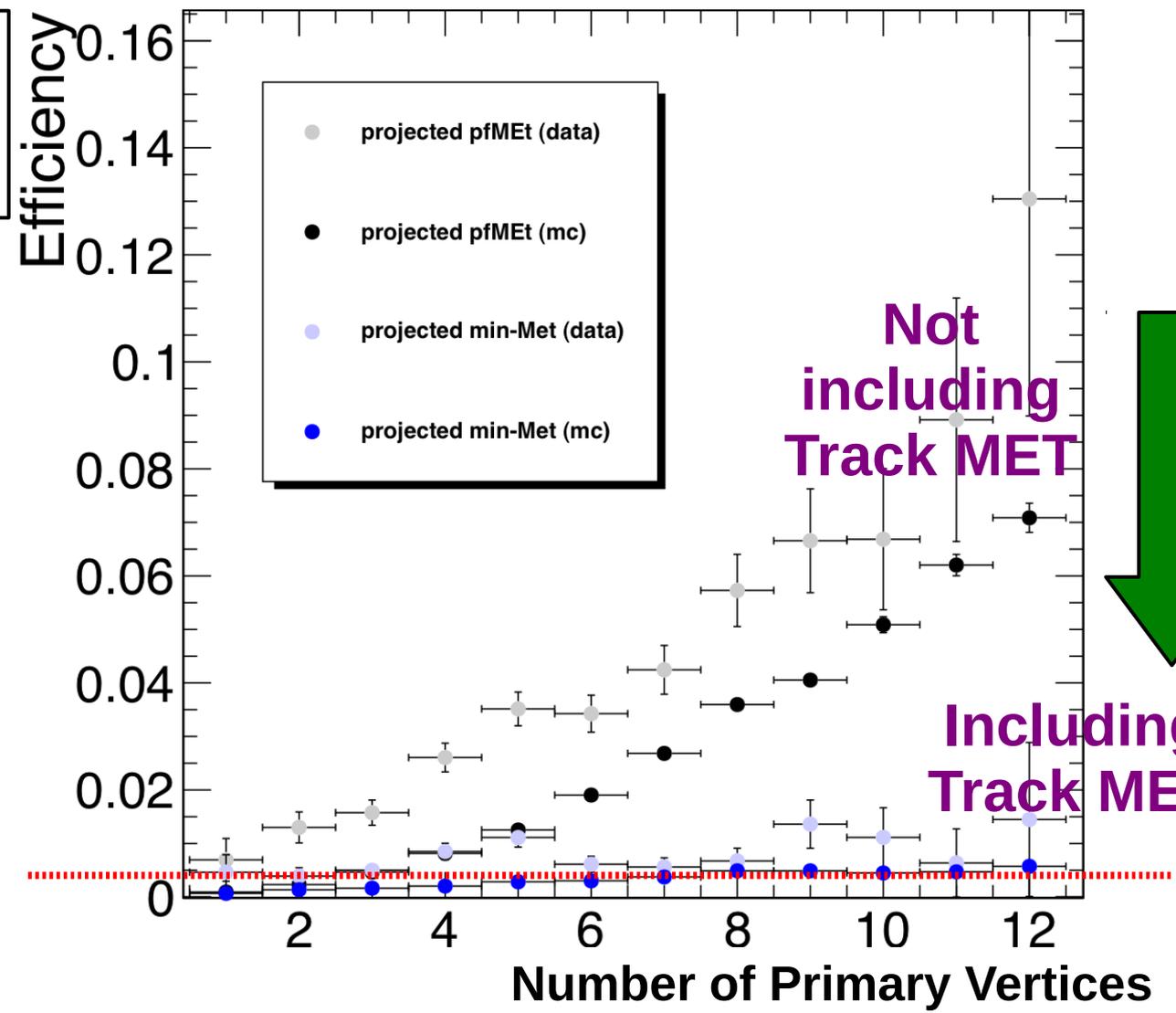




Track MET Performance

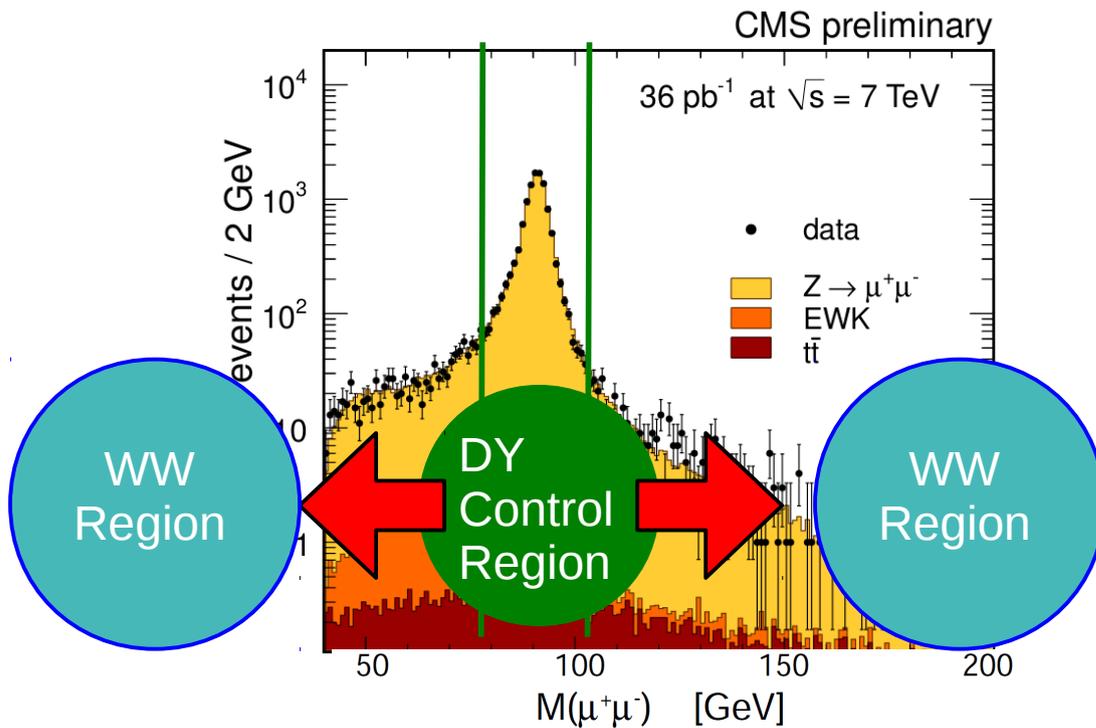
**MET Cut
Efficiency for
DY Background**

**Need at least this
level of suppression**



Estimating Drell-Yan Background

Make use of well known DY mass spectrum to extrapolate



Systematic Uncertainties

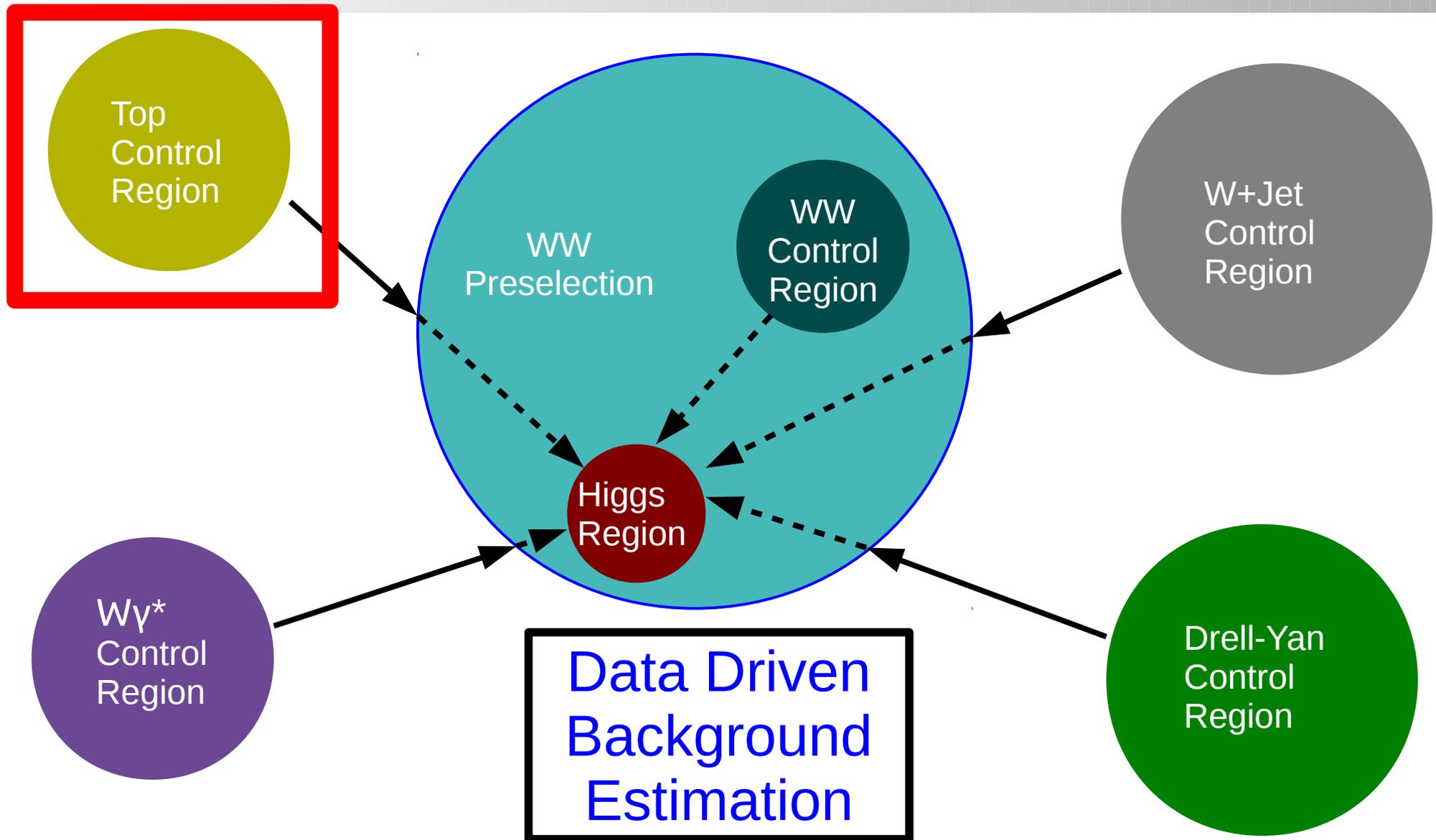
- (1) Control region counts
- (2) Extrapolation (in MET)

- Typically very large
~ **O(50% - 100%)**
- The **limiting factor**
in ee & $\mu\mu$ channels

For low mass Higgs: ~20% of total bkg in ee/ $\mu\mu$



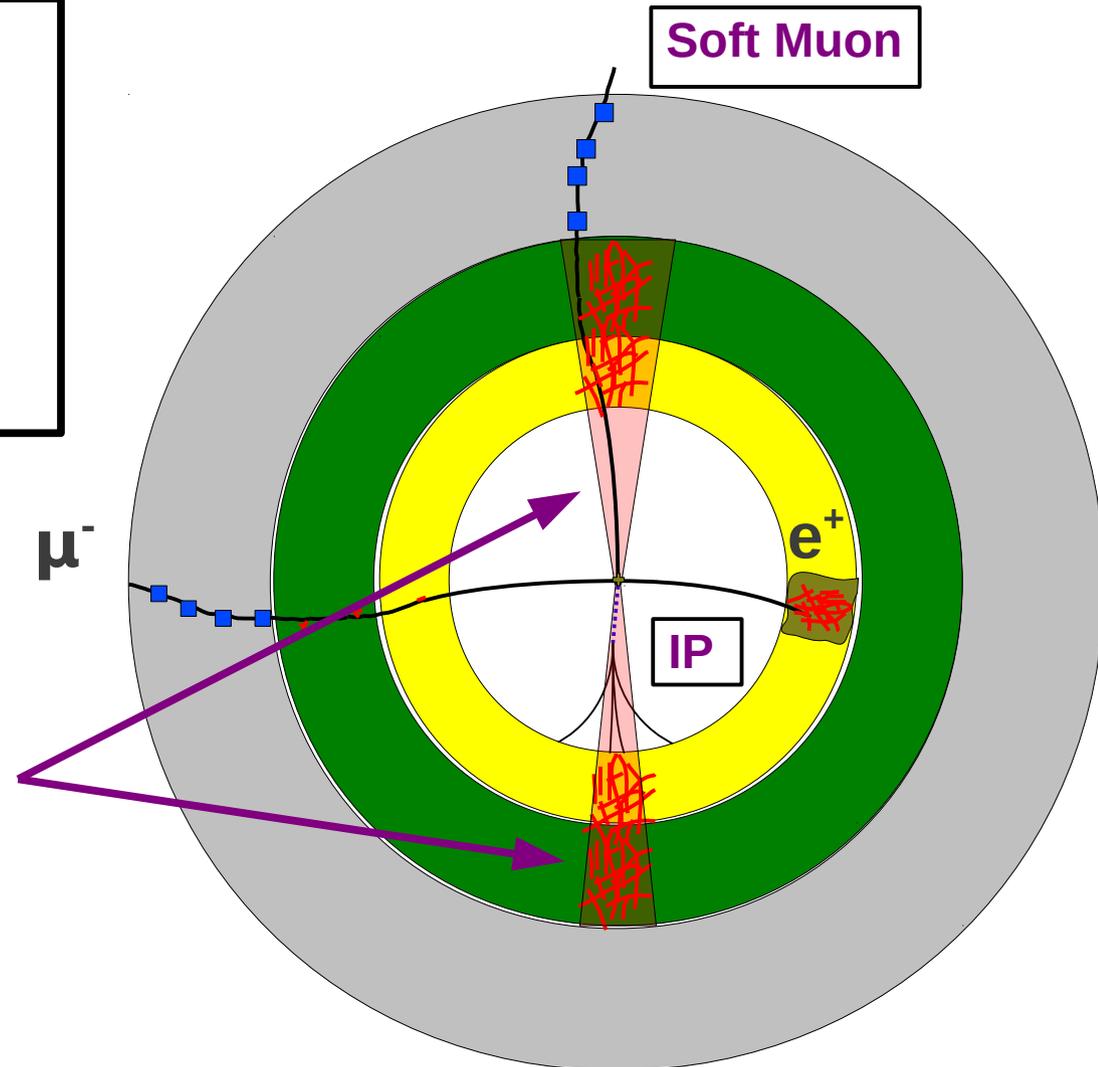
Establishing Control of Backgrounds



Top Background

$t\bar{t} \rightarrow WWbb$
cross section more than
2 orders of magnitude
larger than signal

The only extra feature in
the events are **2 b-jets**

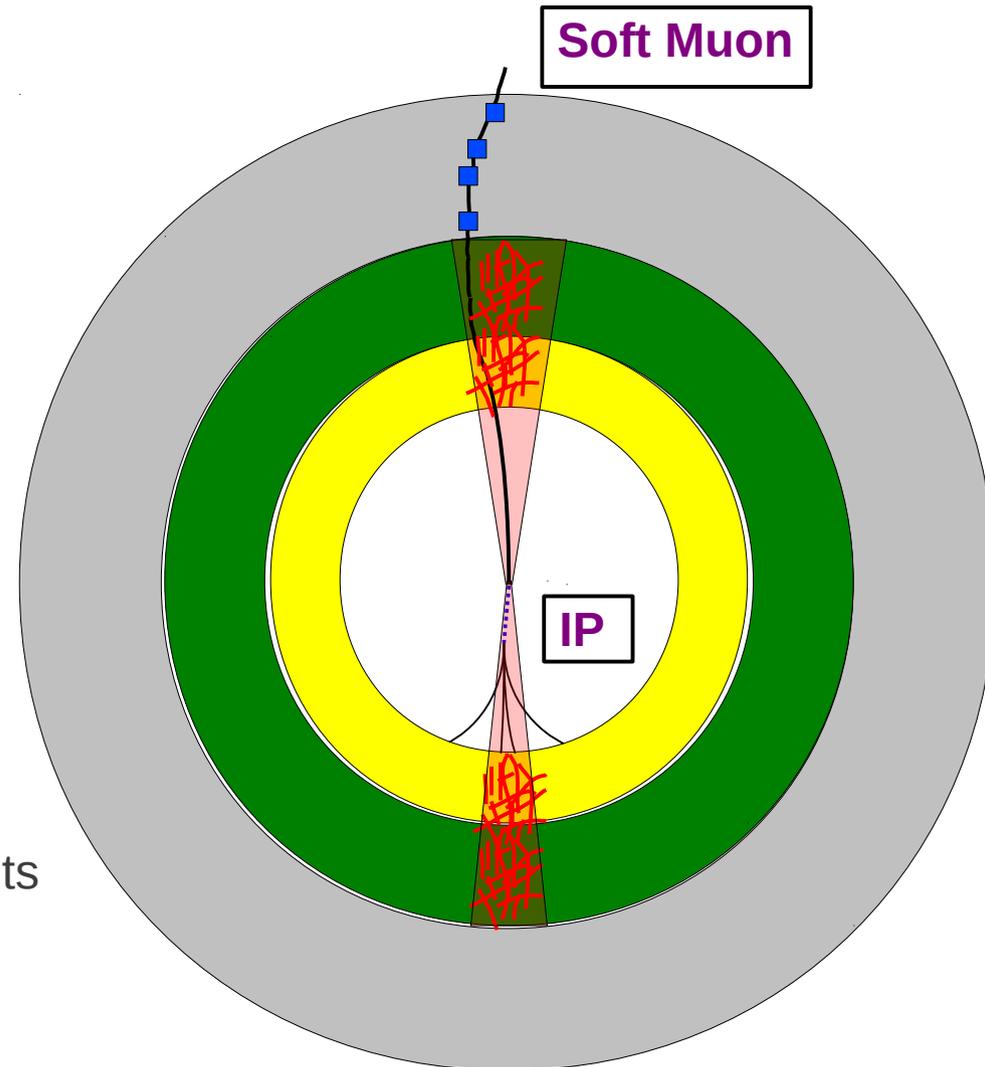


Top Background

The only extra feature in the events are **2 b-jets**

(1) Number of Jets

- Reconstruct and identify jets with $p_T > 30$ GeV
- Categorize into events with:
 - 0 Jet
 - 1 Jet
 - 2 Jet
 - Top background too large
 - Focus on VBF Higgs applying cuts on M_{jj} and $\Delta\eta_{jj}$



Top Background

The only extra feature in the events are **2 b-jets**

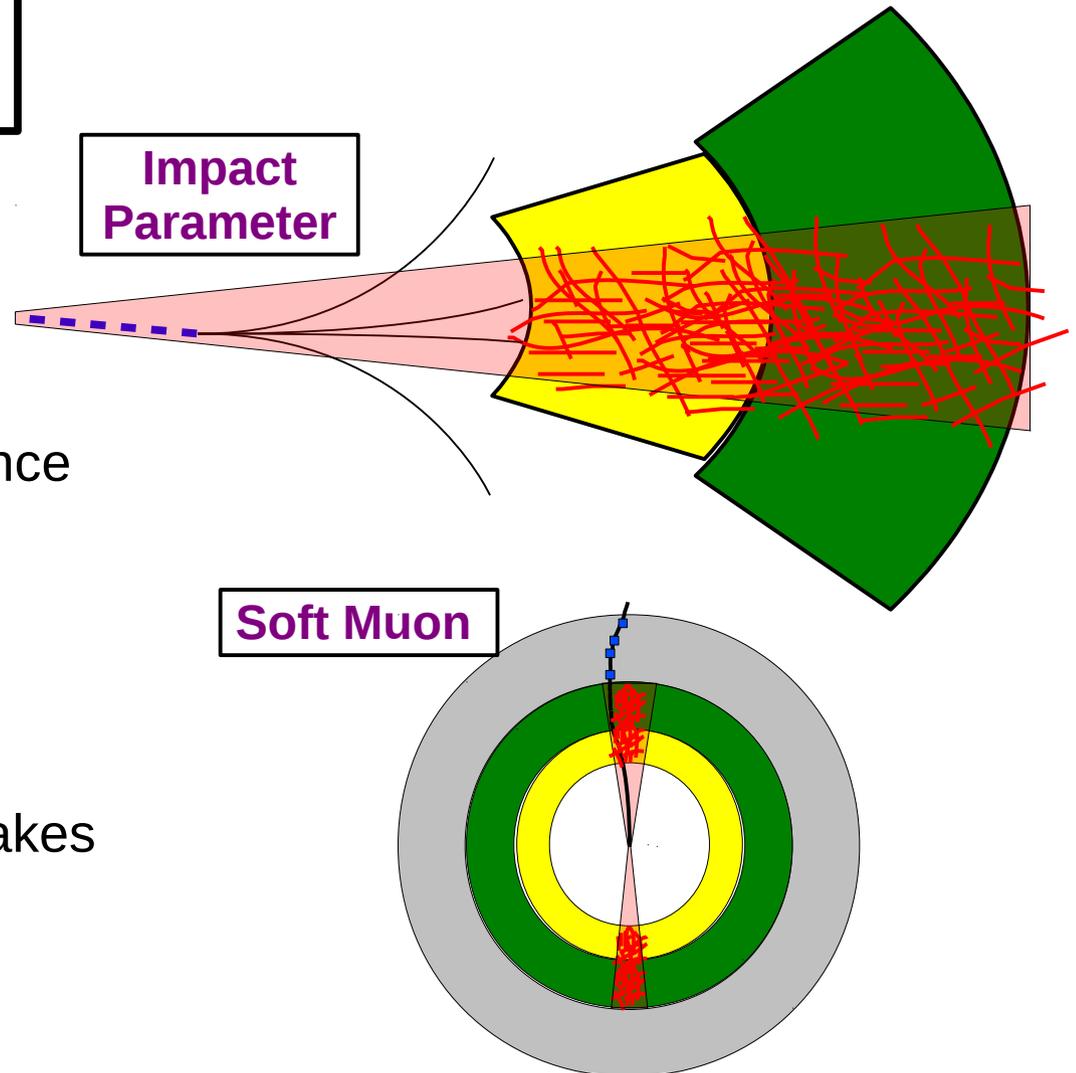
(2) Top-Tagging

(a) B-Tagging

- Use impact parameter significance of tracks inside jets

(b) Soft-Muon Tagging

- Look for additional muons (not necessarily isolated)
- Tight quality cuts to suppress fakes

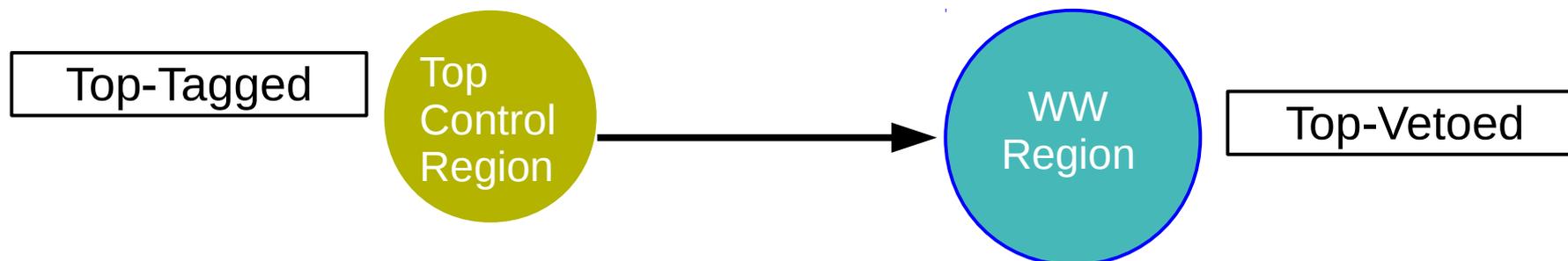


Estimating Top Background

“Top Bkg” consists of $t\bar{t}$ and tW

Measured in orthogonal top enhanced data samples

- Data Driven Estimation:
Extrapolate in top-tagging efficiency



Systematic Uncertainties

- Control region counts
- W+Jet background estimate in top control region
- Extrapolation (top-tagging efficiency)

For low mass Higgs: ~5%, 30%, 45% of total bkg in 0-Jet, 1-Jet, 2-Jet

Some Important Backgrounds May Not Even Be Obvious

$$W + \gamma^* \rightarrow l\nu ll$$

Second lepton from γ^* remains unidentified for any of these scenarios:

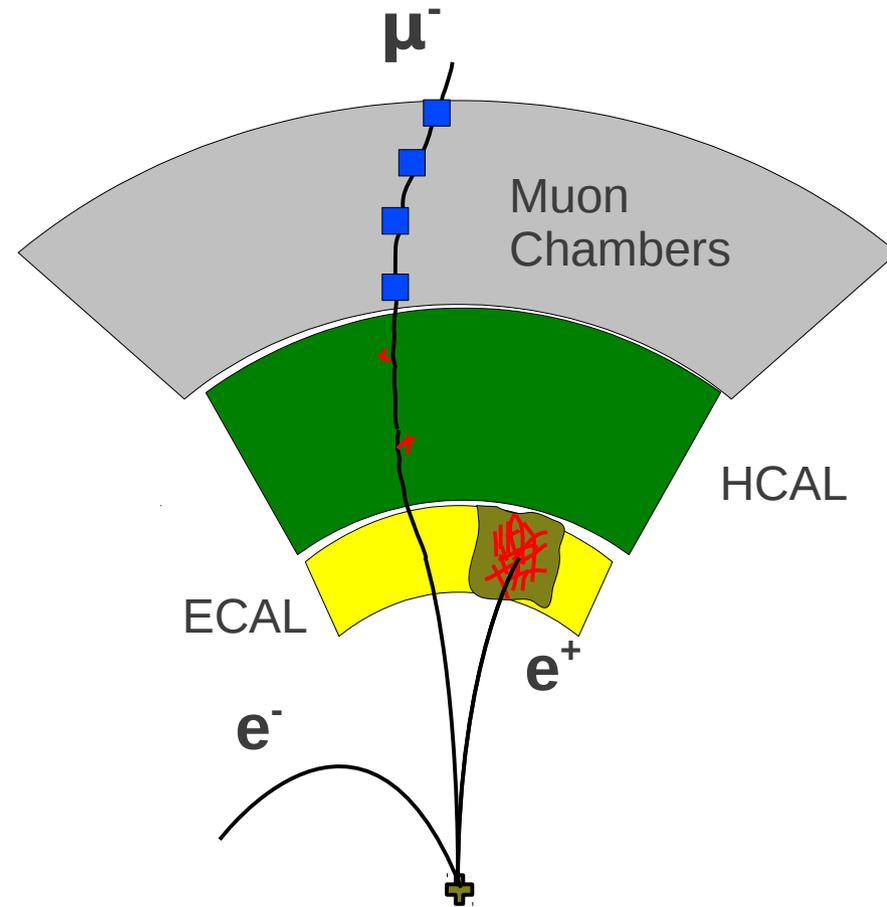
- very low p_T
- outside acceptance
- falls in same energy cluster as first electron [electron]

• Phase space with γ^* mass near kinematic threshold has large cross section $O(5 \text{ pb}) \sim 20x$ signal !



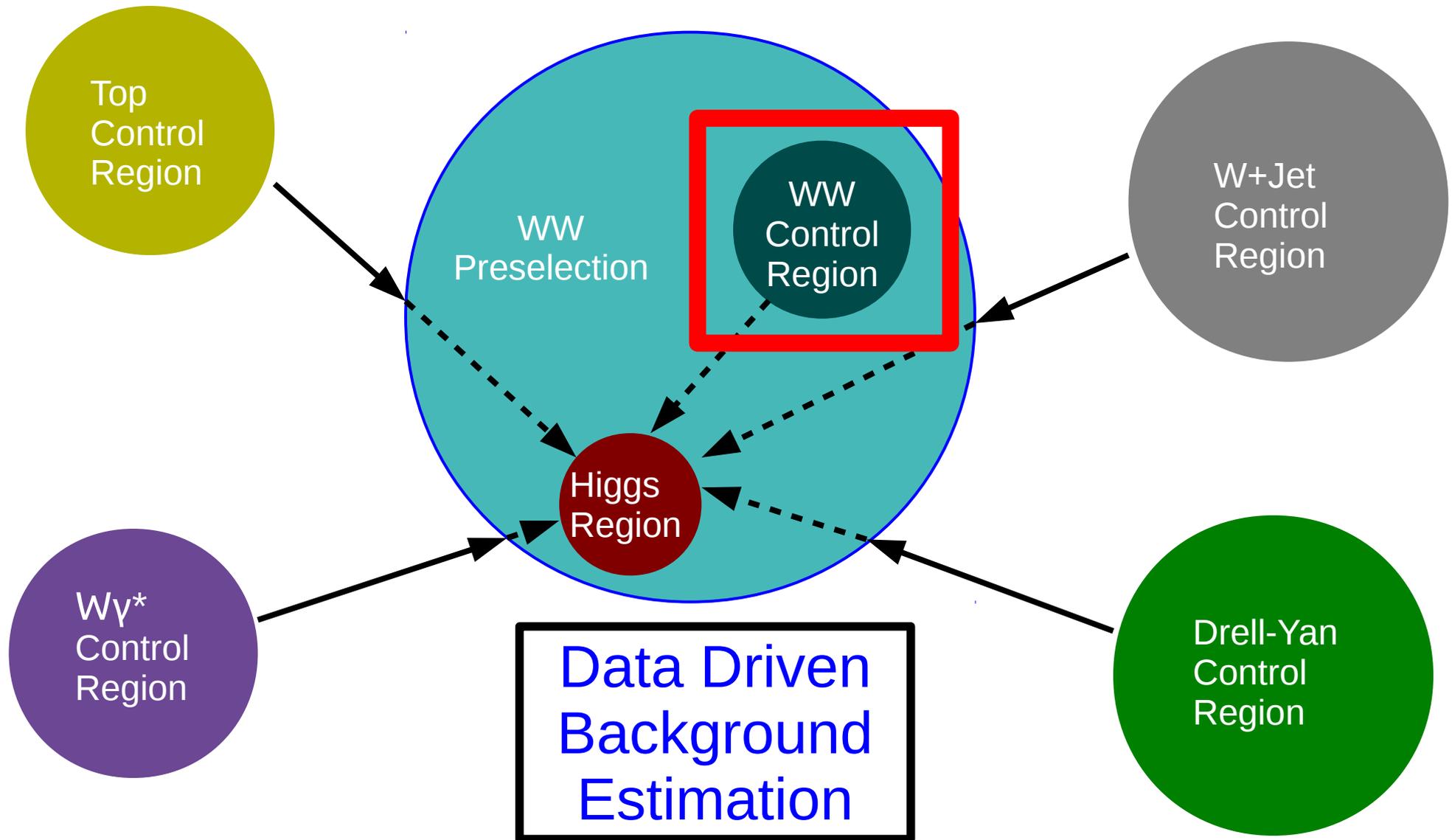
A subtle background...

For low mass Higgs: ~5% total bkg





Establishing Control of Backgrounds



WW Background

Non-resonant WW production is the largest background

- Good precision of theoretical predictions
- But..... need to disentangle WW from Higgs

For low mass Higgs:
~70% total bkg

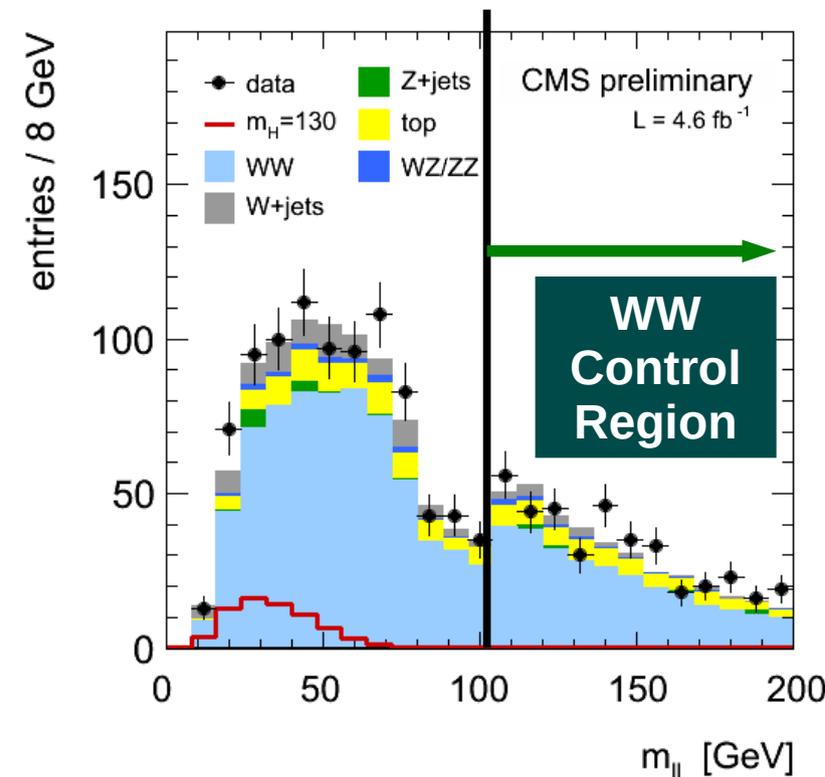
Data driven estimate of normalization:

- Measure cross section in signal-free region ($m_{\parallel} > 100$ GeV)

Note that **ALL** other backgrounds must be well controlled first

- Extrapolate to signal region with Monte Carlo

Only works for low mass Higgs ($m_H < \sim 200$ GeV)



Analysis Strategy

(1) WW Pre-selection

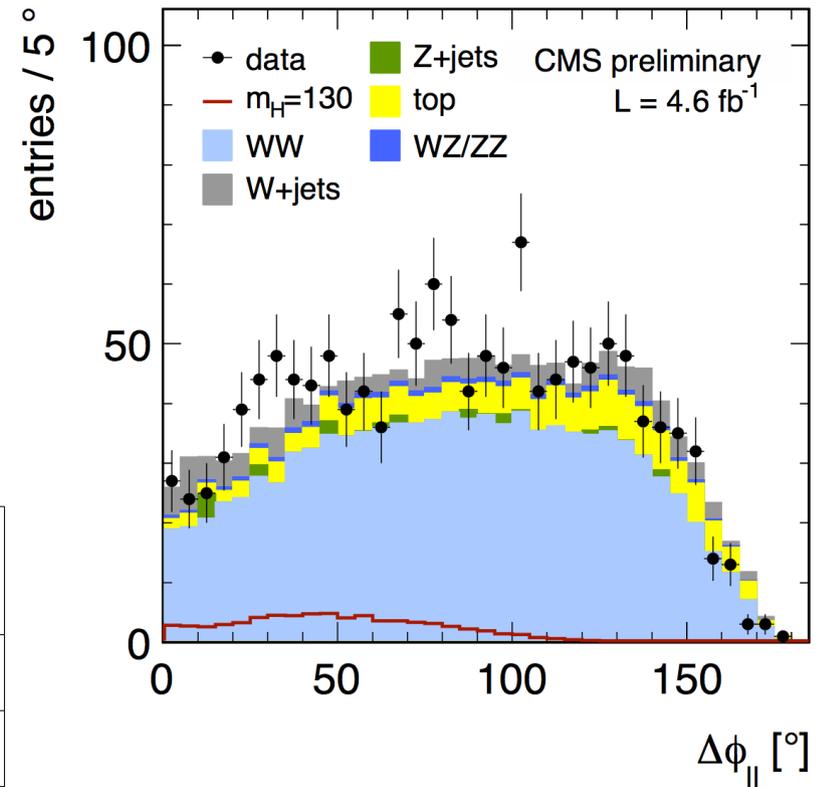
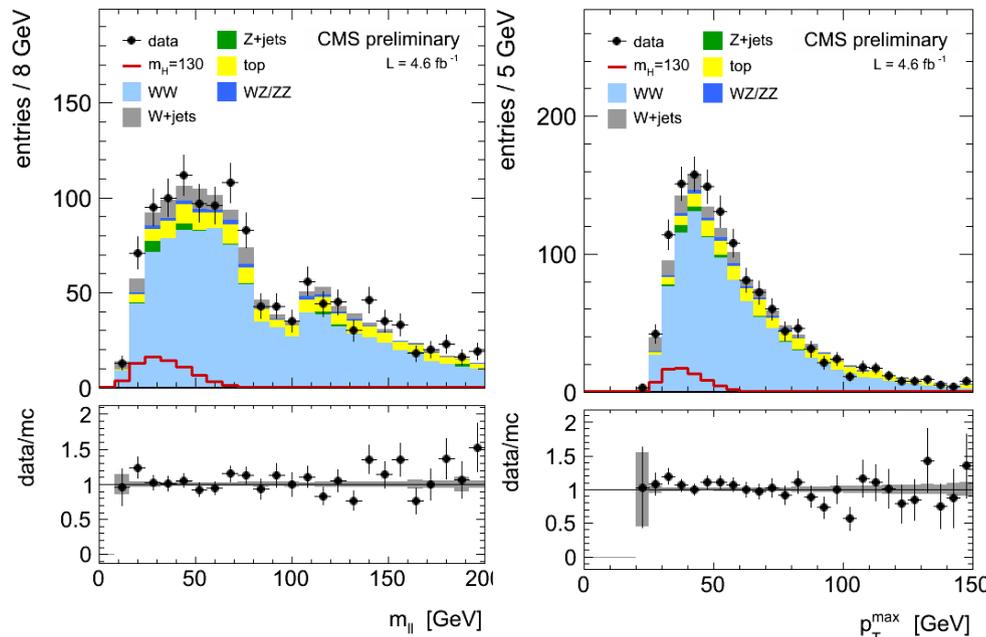
- Establish the WW signature
- **Establish control on estimates of main backgrounds**

(2) Higgs Selection

- Discriminate Higgs against WW background
 - Cut-Based selection
 - MVA discriminator

Control of WW Region

Background prediction and data agree well



	Observed Data	Background Estimate
0-Jet	1359	1364.8 ± 9.3
1-Jet	909	951.4 ± 9.8
2-Jet	703	714.8 ± 13.5

Analysis Strategy



(1) WW Pre-selection

- Establish the WW signature
- Establish control on estimates of main backgrounds



(2) Higgs Selection

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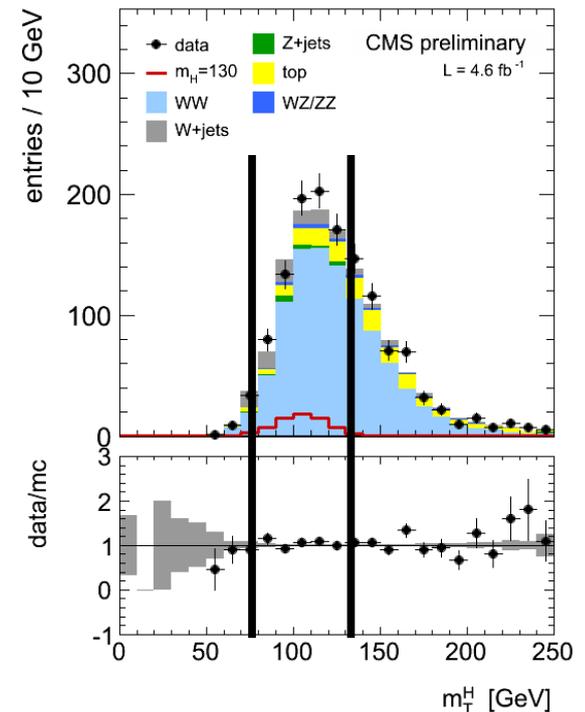
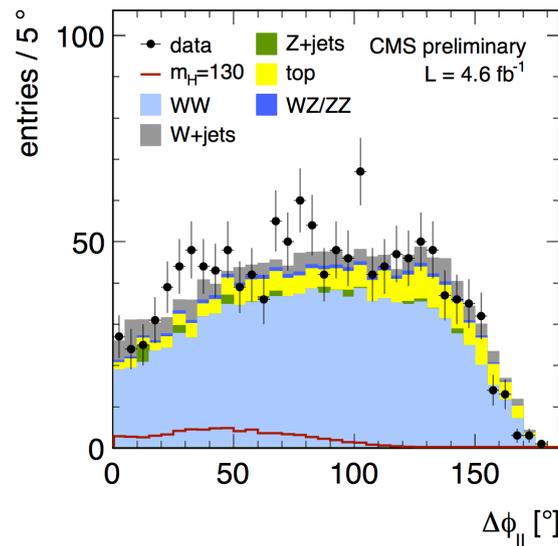
Higgs vs WW Discrimination

- Event objects are identical
- Must rely on kinematical differences

Higgs is a spin 0 scalar

Transverse Mass

- Decays to longitudinally polarized W's yield angular correlations of the 2 leptons
- Higgs mass dependent



Not an easy job!

Signal Event Selection

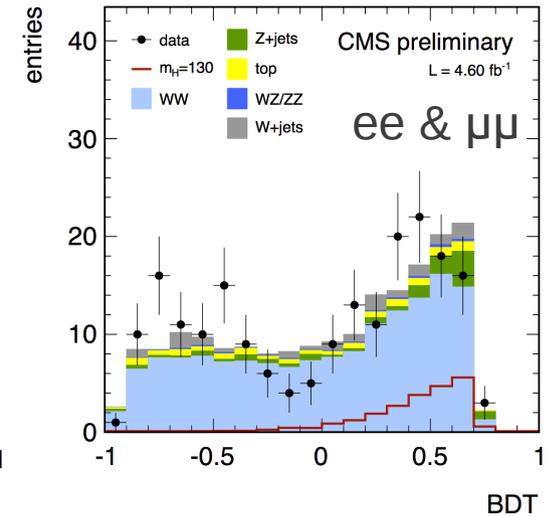
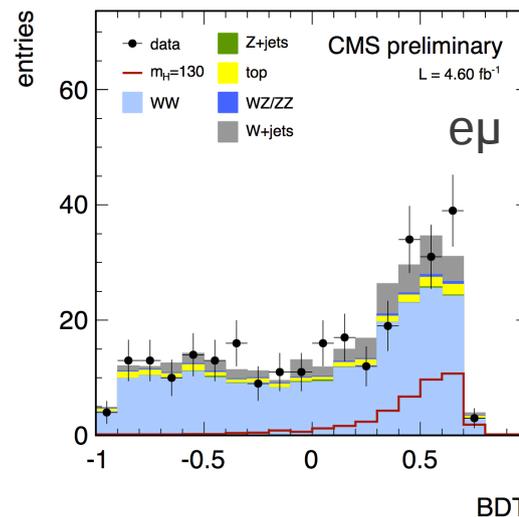
Two strategies to extract Higgs signal

(1) Cuts on discriminating kinematic observables to extract signal

m_H [GeV/c ²]	$p_T^{\ell, \max}$ [GeV/c]	$p_T^{\ell, \min}$ [GeV/c]	$m_{\ell\ell}$ [GeV/c ²]	$\Delta\phi_{\ell\ell}$ [dg.]	$m_T^{\ell\ell E_T^{\text{miss}}}$ [GeV/c ²]
	>	>	<	<	[]
120	20	10(15)	40	115	[80,120]
130	25	10(15)	45	90	[80,125]
160	30	25	50	60	[90,160]
200	40	25	90	100	[120,200]
250	55	25	150	140	[120,250]
300	70	25	200	175	[120,300]
400	90	25	300	175	[120,400]

(2) Boosted Decision Tree trained against WW

- Binned Shape Analysis





Systematic Uncertainties

- Must parameterize and propagate lack of knowledge about background and signal yields and distributions
- Systematic uncertainties are propagated for a large number of sources :

lepton energy/momentum scale and resolution, lepton selection efficiency, luminosity, MET resolution, jet energy scale, MC statistics, missing higher order corrections, parton shower model, fake rate extrapolation, fake lepton jet spectrum, DY extrapolation in MET, single top – $t\bar{t}$ interference, DY $\rightarrow \tau\tau$ estimation, ...

..... But are dominated by background estimation systematics

Background Systematic Uncertainties

- Some feeling on the size of background systematics...

Process	$\delta B/B$	$\delta B/S_{(m_H = 120 \text{ GeV})}$
W+Jets	36%	40%
Drell-Yan $\rightarrow ee/\mu\mu$	70%	150%
Top 	25%	8%
WW 	13%	70%



Decreases statistically with increasing luminosity

What's the bottom line?

- WW is dominant now ... but will decrease with more data
- W+Jets will be dominant soon
- Drell-Yan dominates **ee/μμ**



Signal Systematic Uncertainties

- To set limits on production cross section, must estimate uncertainties on the signal
- Main systematic effects:

(1) Production Cross Section

- Missing higher order corrections : ~12%
- Parton Distribution Functions : ~8%

(2) Jet Bin Migration

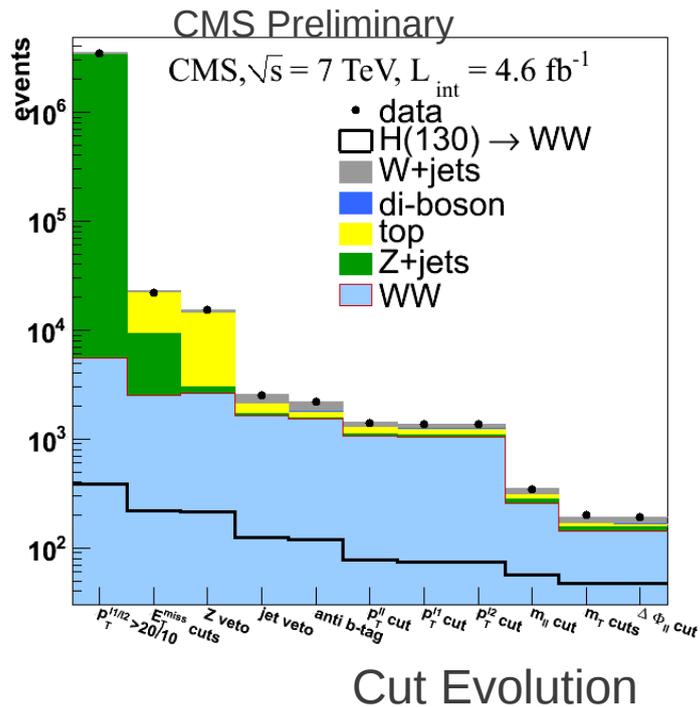
- | | 0-Jet | 1-Jet | 2-Jet (VBF) |
|------------------------------------|--------|--------|-------------|
| • Missing higher order corrections | : ~10% | , ~30% | , ~20% |
| • Parton Shower Model | : ~6% | , ~10% | , ~30% |

Now...Search for the Higgs

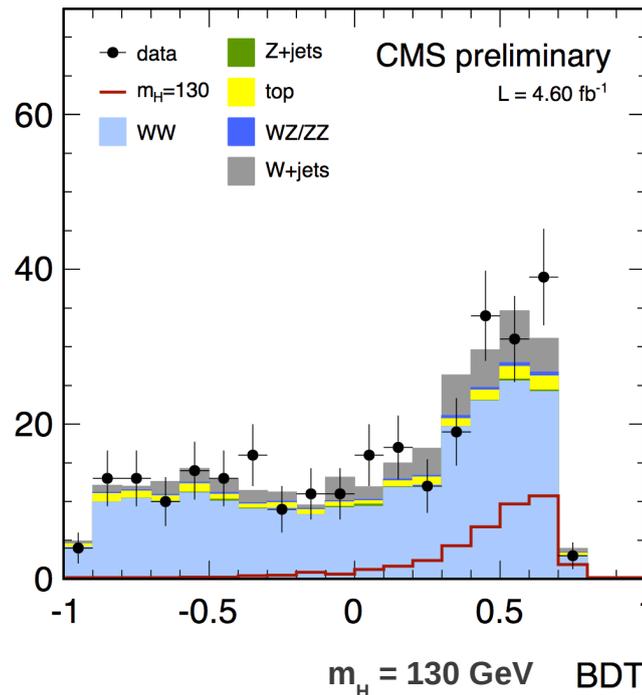
(1) Cut - and - Count

(2) MVA Shape Analysis

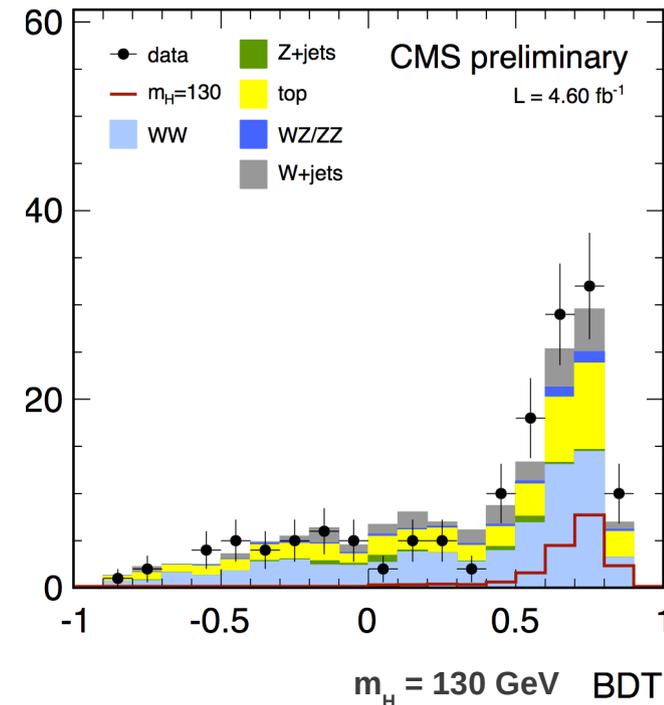
$m_H = 130$ GeV



$e\mu$ 0-Jet Bin



$e\mu$ 1-Jet Bin





Statistical Analysis

For a quantitative evaluation of a search result...

We must do statistical analysis

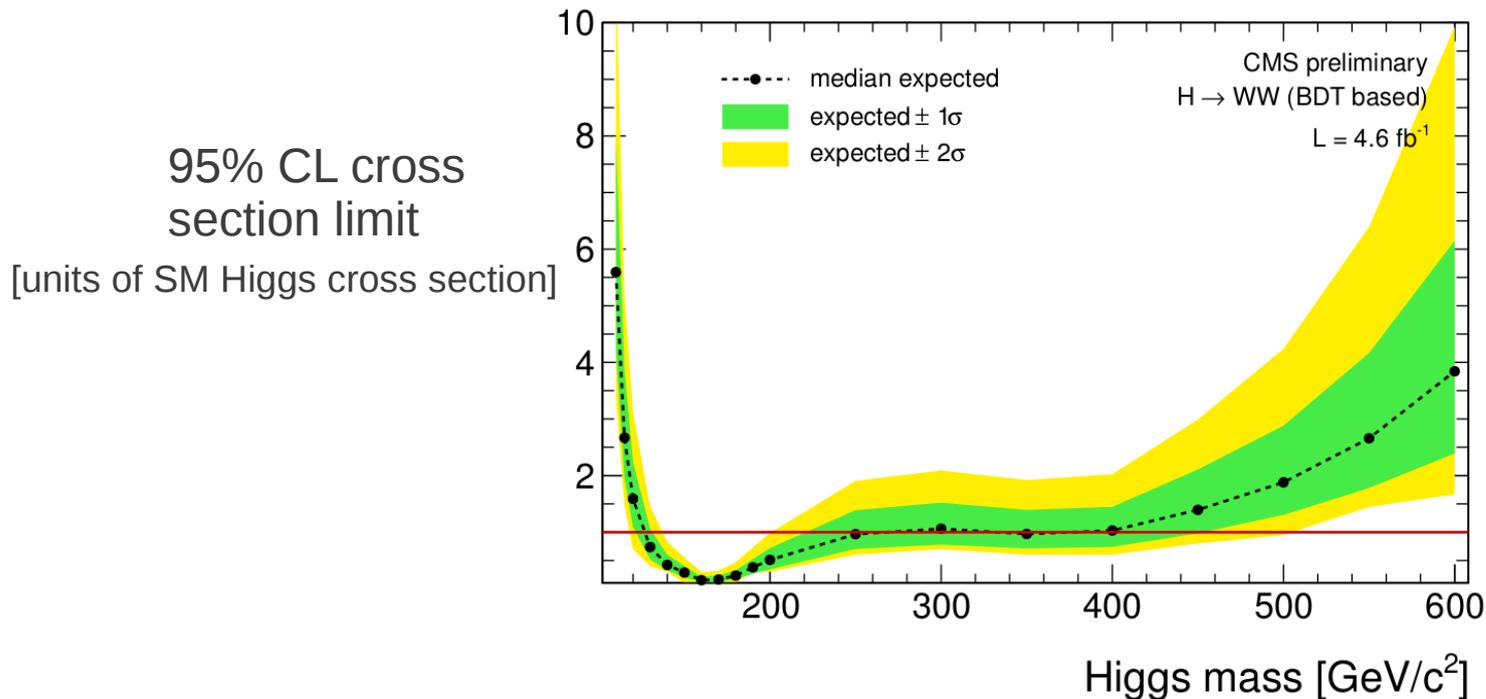
- Historically multiple methods have been used for various reasons
- CMS and ATLAS have a commonly agreed method: “**CL_s-LHC**”
 - Allows for simple comparison of results

...with a number of desirable statistical features

Essentially: Likelihood ratio method in the Feldman-Cousins approach

Expected Sensitivity

How sensitive do we expect to be to a Standard Model Higgs Boson?



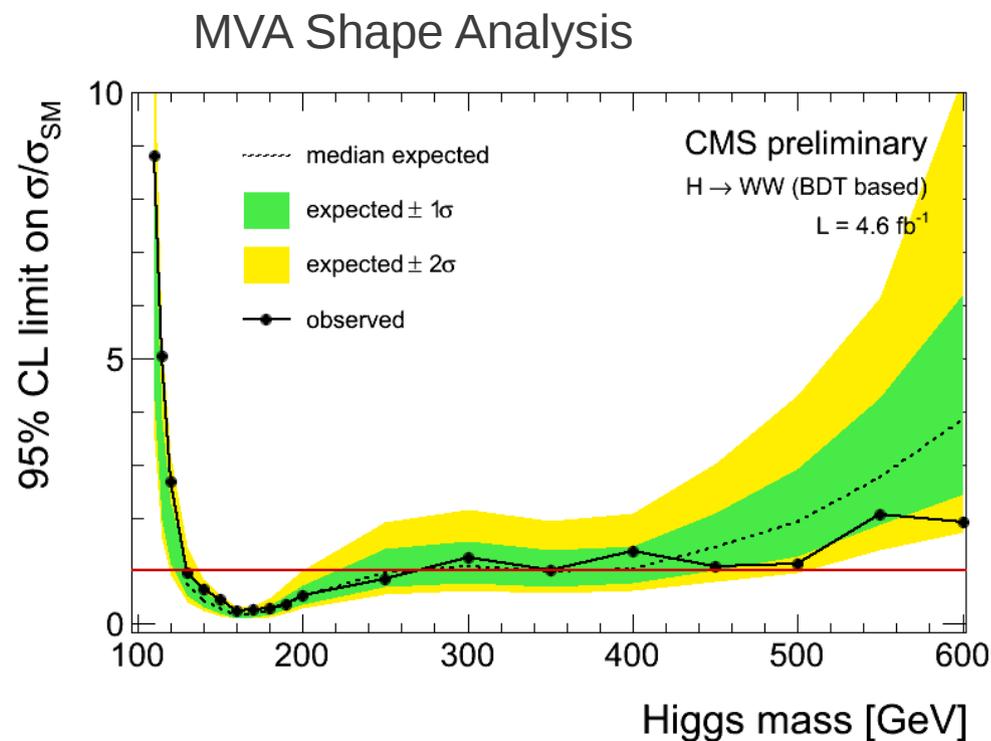
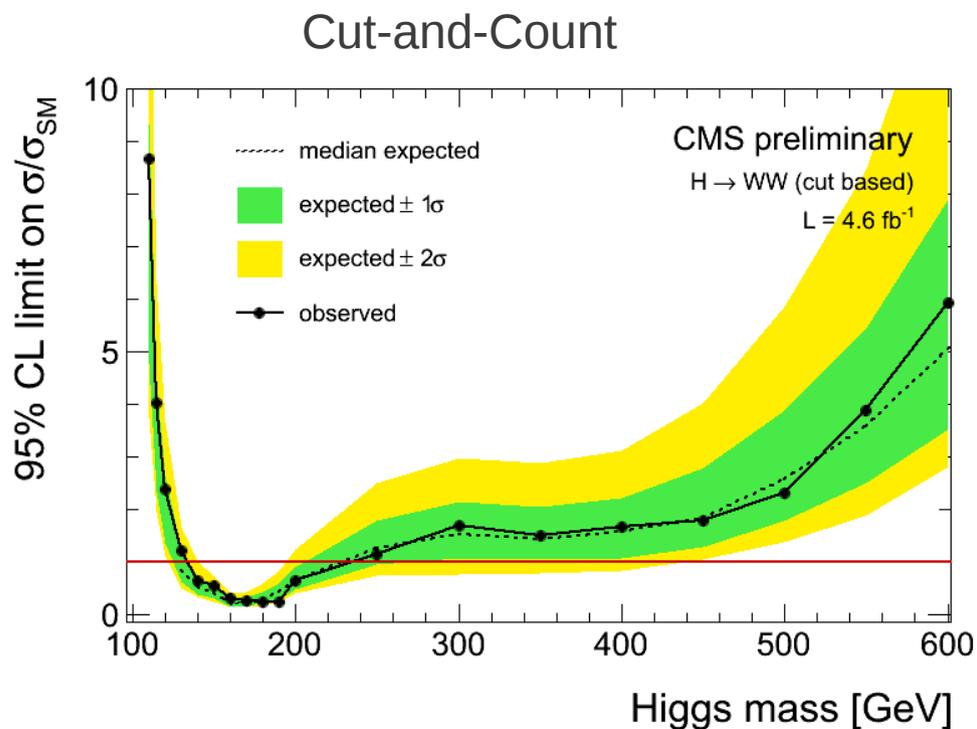
SM Higgs @ given mass is excluded if the limit is below 1.0

- On average can exclude Standard Model Higgs Production with masses in the range **[127 GeV, 270 GeV]**

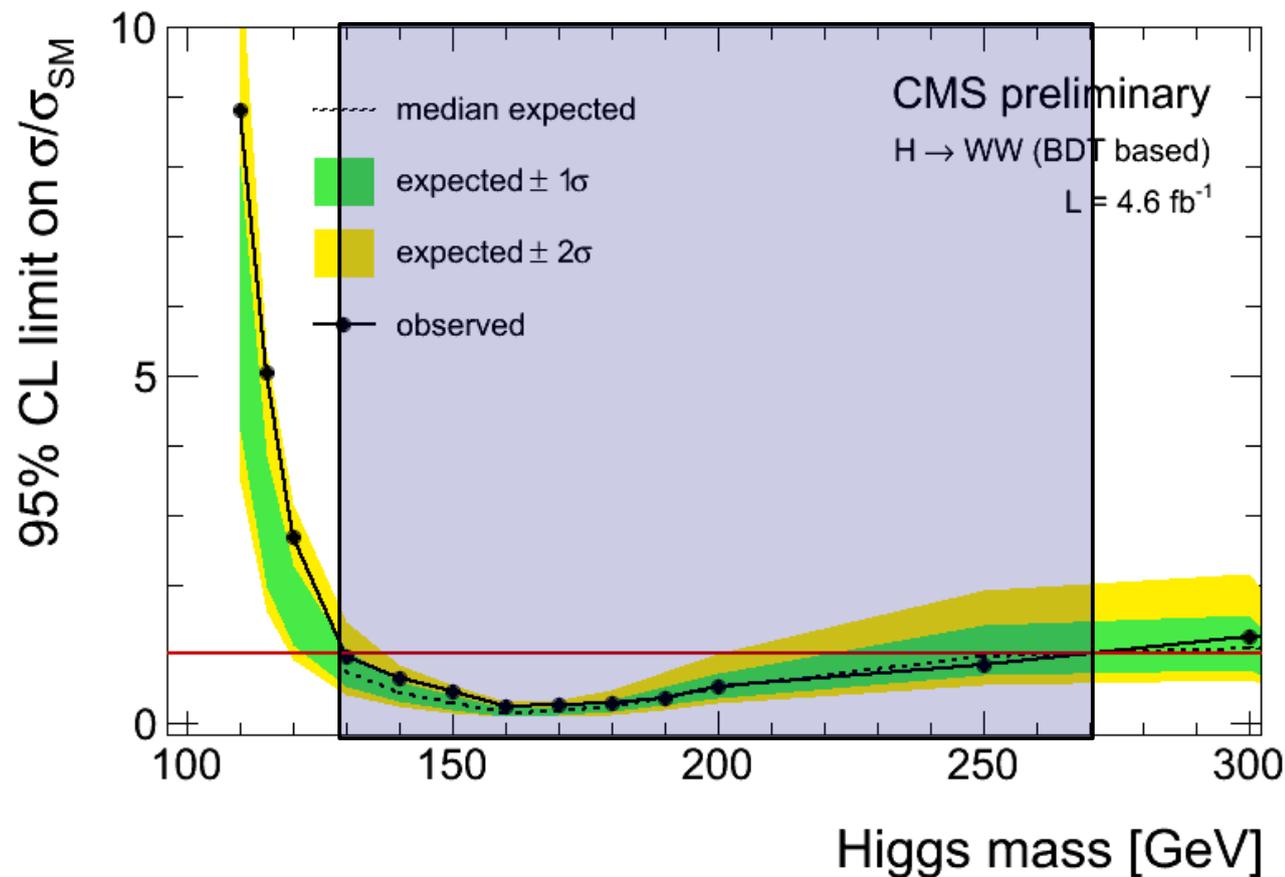


Higgs Cross Section Limits : 4.6 fb^{-1}

- MVA shape analysis generally $\sim 15\text{-}20\%$ better sensitivity
 - At very high masses the increase is larger
- No statistically significant deviation from expectations



Higgs Cross Section Limits

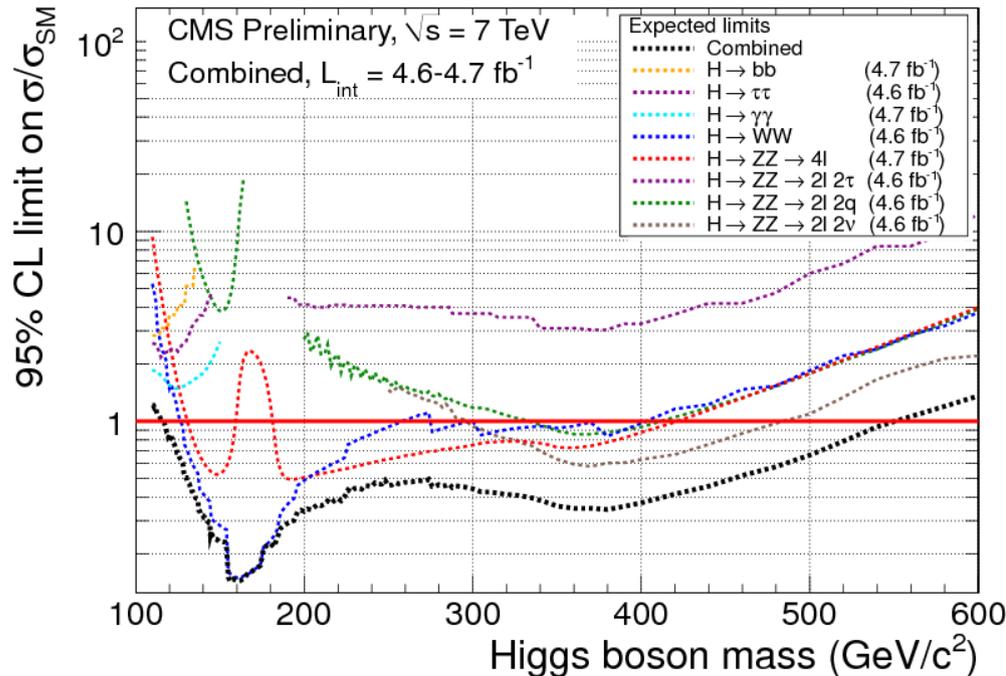


- Exclude Standard Model Higgs Production with masses in the range **[129 GeV, 270 GeV]**

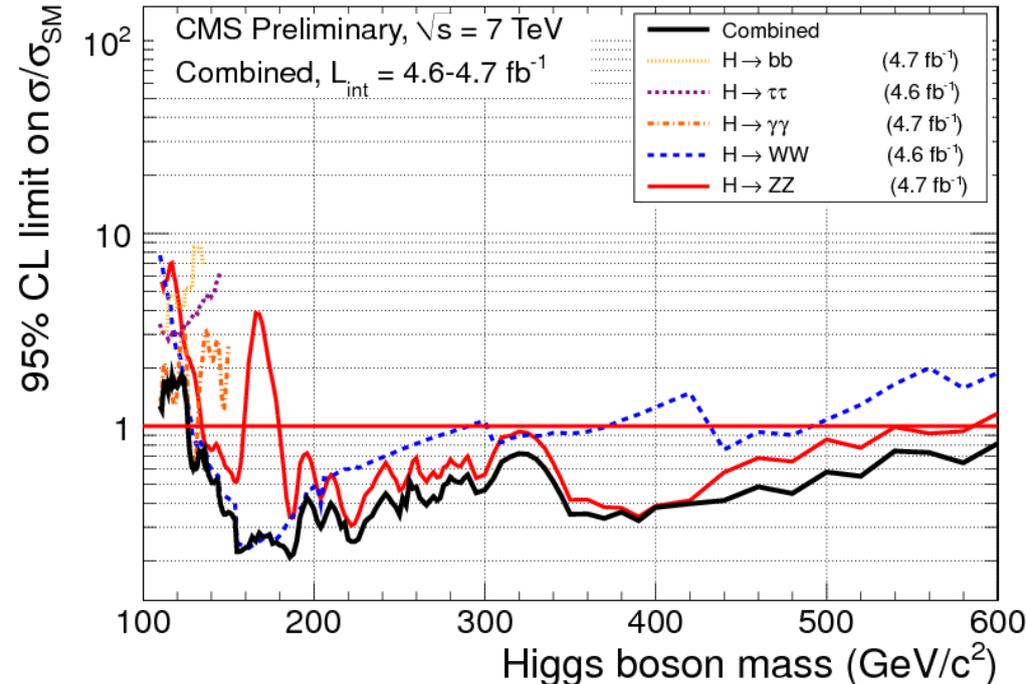


CMS Combined Higgs Limits

Expected Limits



Observed Limits



Combining all CMS Higgs channels yields expected exclusion mass range of **[117 GeV, 543 GeV]** and observed range of **[127 GeV, 600 GeV]**

Note that the WW channel is the most sensitive channel from 117 GeV to 200 GeV



Summary

- Presented search for the Higgs boson decaying to WW at CMS using 4.6 fb^{-1}
 - In the absence of signal, expected to exclude Higgs @ 95% confidence level in the range $[127, 270] \text{ GeV}$
- No statistically significant excess was found
 - Standard Model Higgs excluded @ 95% confidence level in the mass range $[129, 270] \text{ GeV}$
 - Combined with other CMS channels exclude $[127, 600] \text{ GeV}$



Sneak Preview @ 2012

LHC expected to deliver another $\sim 15 \text{ fb}^{-1}$ @ **8 TeV**

Pileup to increase
by factor of 2!

Big Challenges
Ahead

Together with ATLAS, likely to
say something much more
definitive this year

An exciting year ahead!



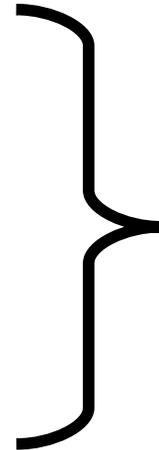
Backup



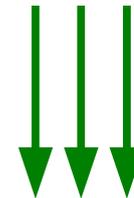


Triggers

- LHC has a bunch crossing rate of ~ 15 MHz
- CMS Level1 Trigger Rate : 100kHz
 - Rejection factor of 150
 - $1 \mu\text{s}$ decision time
- High Level Trigger Rate : 300 Hz
 - Another rejection factor of 300



Total rejection factor $\sim 5 \times 10^4$



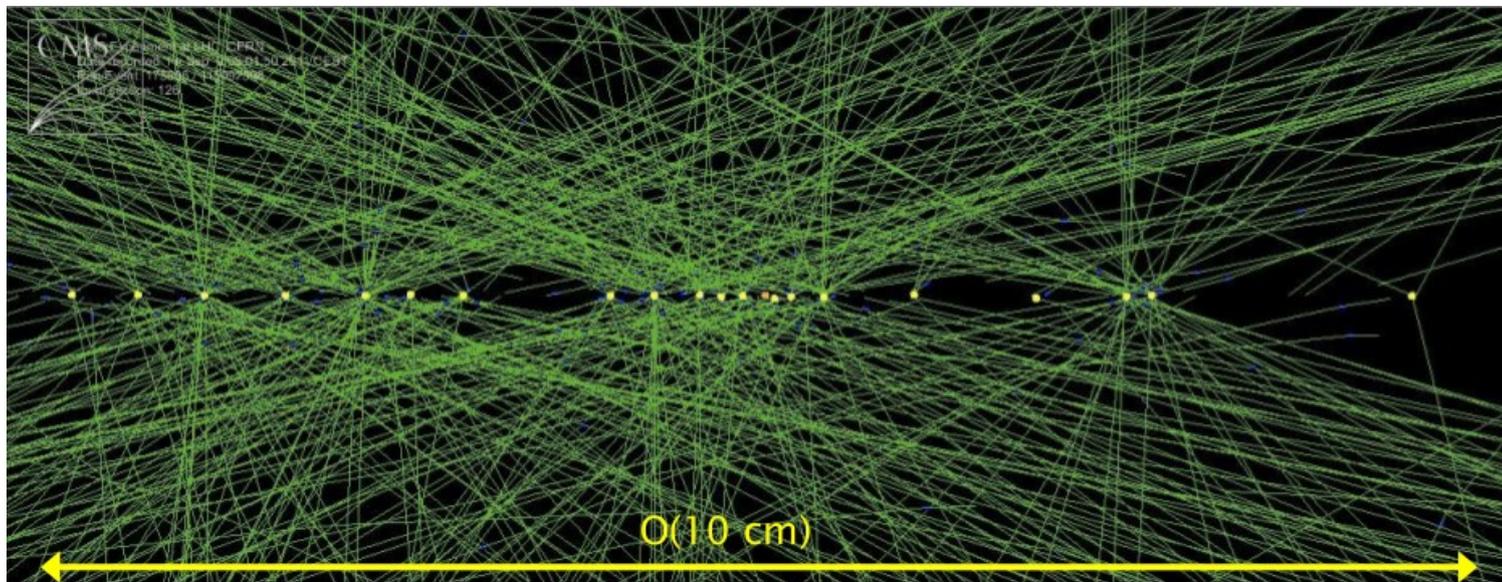
Triggers are crucial at a hadron collider

Signal triggers not the only important triggers

- *Suite of triggers needed to understand and control backgrounds*

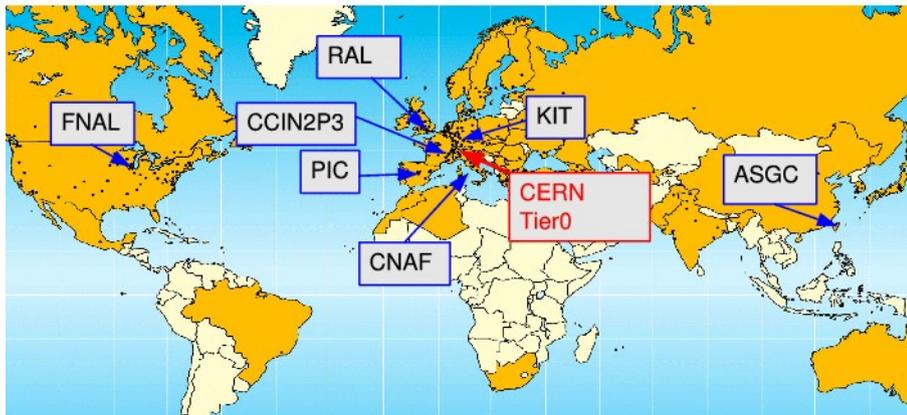
Pileup @ LHC

- Average of 10 interactions per bunch crossing



CMS Computing

- Multi-Tiered Distributed Computing Infrastructure
 - Tier-0 @ CERN : Prompt Reconstruction
 - Tier-1 (7 sites) : Re-processing
 - Tier-2 (~50 sites) : MC Production & Analysis
- Transfer Operations responsible for monitoring transfers to/from all sites and global management of CMS data



Tier0 Center @ CERN

Prompt Data Reconstruction

7 Tier1 Centers

KIT PIC CCIN 2P3 CNAF ASGC RAL FNAL

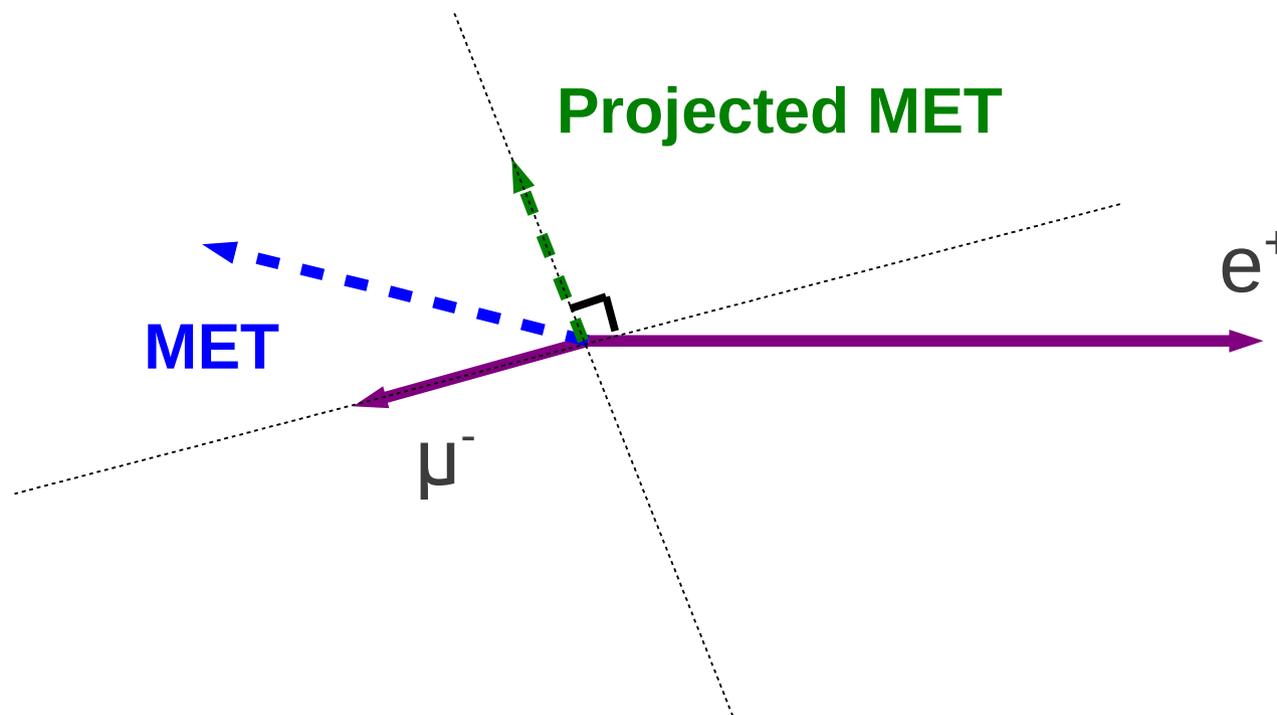
Data distributed to T1 centers for storage and further processing

Prompt Skimming @ Tier1 Centers

Distribute to Tier2 Centers for analysis

Drell-Yan $\rightarrow \tau\tau$: “Projected MET”

- Project MET perpendicular to the closest lepton
 - suppresses $Z \rightarrow \tau\tau$
 - Suppress fake MET from lepton mis-measurement



Z \rightarrow $\tau\tau$ Background

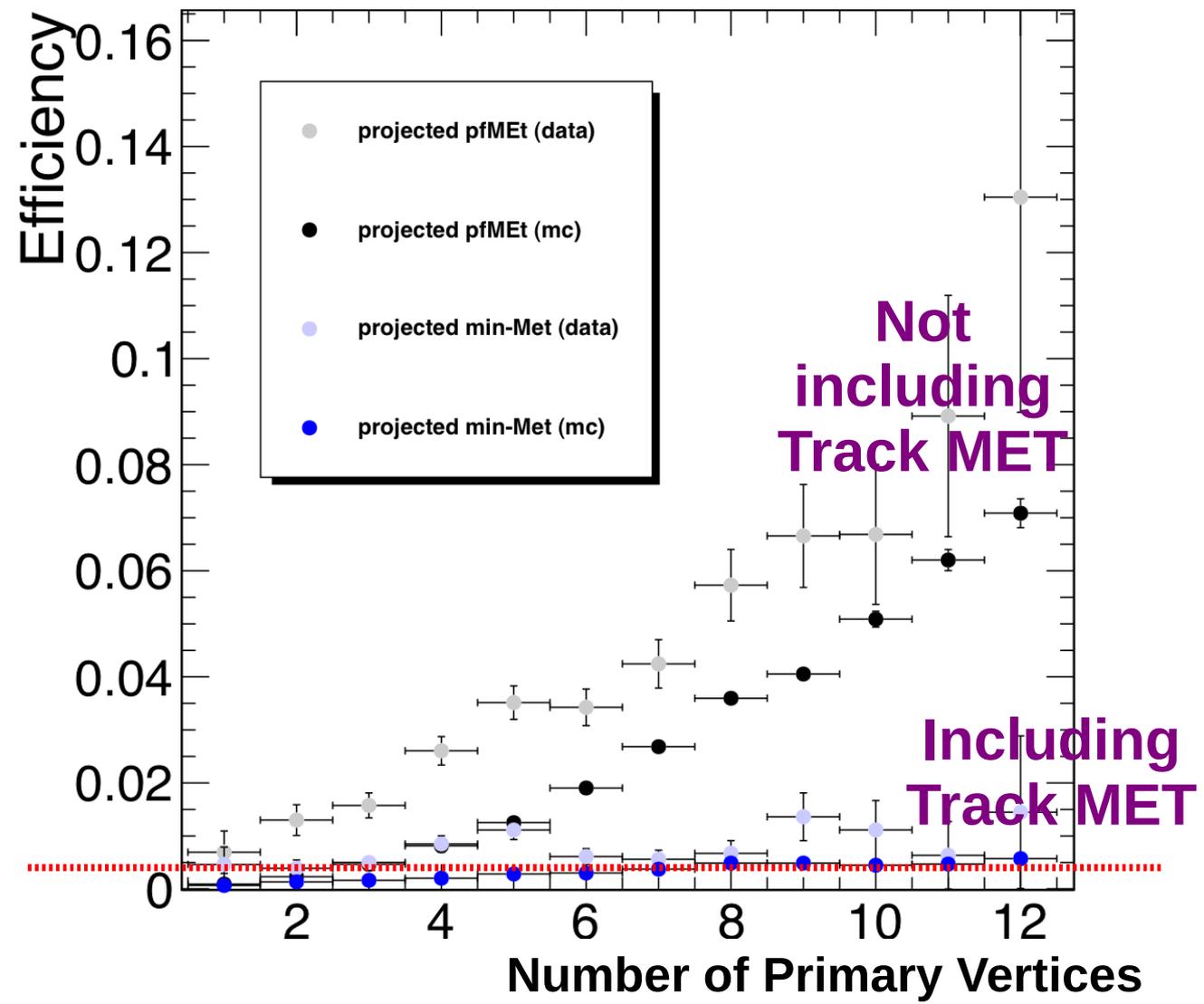
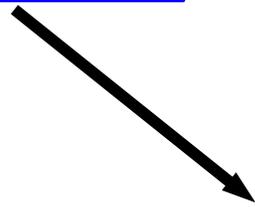
- Embedded Tau Method
 - Take Z $\mu\mu$ data events
 - Remove signature of muons and replace it at the reconstruction level by the signature of a leptonic tau decay
- Obtain data-driven description of the recoil and thus the MET resolution
- Monte Carlo tests indicate small systematic uncertainty : $\sim 10\text{-}20\%$



Track MET Performance

**MET Cut
Efficiency for
DY Background**

**Need at least this
level of suppression**



Top Background

“Top Bkg” consists of $t\bar{t}$ and tW

- Data Driven Estimation:

Extrapolate in top-tagging efficiency

From : top-tagged

To : top-tag vetoed

Measured in top enhanced data samples

- 0-Jet : top-tagging for “soft” jets
- 1-Jet : top-tagging for hard jets
- VBF : top-tagging for most central jet

VBF Cuts

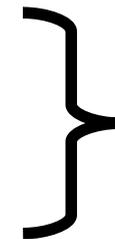
Delta eta < 3.5

M_{jj} < ??

W + γ^* Background Estimation

- Technical Aspects :

- Monte Carlo must cover phase space all the way down to the kinematic threshold ($0.001 \text{ GeV} = 2 \times m_{\text{electron}}$)
- Electron and Muon masses cannot be neglected!



Use
Madgraph
Generator

Data driven estimate of normalization:

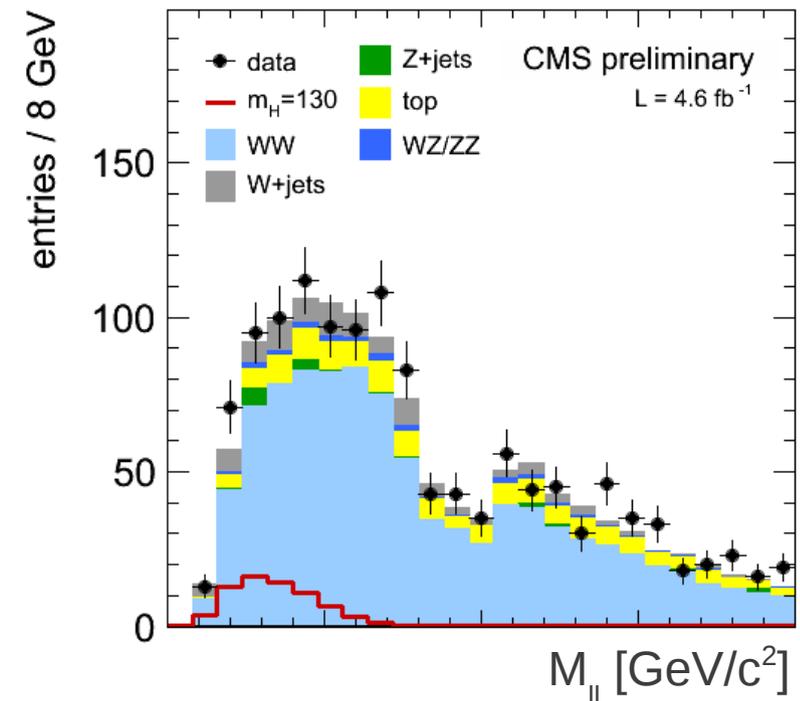
- Measure the cross section in $W\gamma^*$ enhanced region:
 - $l\mu\mu$: $p_T > 10 \text{ GeV}$, special isolation for $\mu\mu$ pair
 - $m_{\parallel} < 20 \text{ GeV}$
 - high MET
 - top vetoed
- Then...extrapolate to signal region with Monte Carlo

For low mass Higgs: ~5% total bkg

WW Background

Systematic Uncertainties

- Control region counts ★
- Background estimates (W+Jets & Top)
- Theory uncertainty of selection efficiency



Control of WW Region

Background prediction and data agree well

Yields :

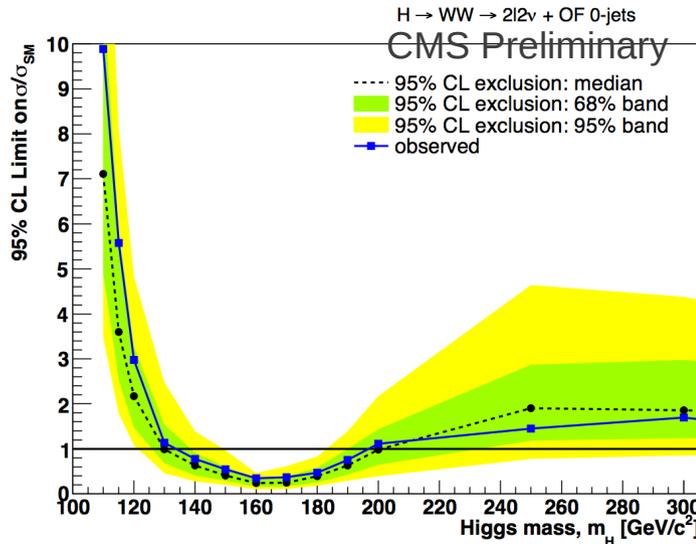
	data	all bkg.	qq \rightarrow W ⁺ W ⁻	gg \rightarrow W ⁺ W ⁻	t \bar{t} +tW	W + jets
0-jet	1359	1364.8 \pm 9.3	980.6 \pm 5.2	58.8 \pm 0.7	147.3 \pm 2.5	99.3 \pm 5.0
1-jet	909	951.4 \pm 9.8	416.8 \pm 3.6	23.8 \pm 0.5	334.8 \pm 3.0	74.3 \pm 4.6
2-jet	703	714.8 \pm 13.5	154.7 \pm 2.2	5.1 \pm 0.2	413.5 \pm 2.7	37.9 \pm 3.6

	WZ/ZZ	Z/ γ^* \rightarrow l^+l^-	W γ	Z/ γ^* \rightarrow $\tau^+\tau^-$
0-jet	33.0 \pm 0.5	16.6 \pm 4.0	26.8 \pm 3.5	2.4 \pm 0.5
1-jet	28.7 \pm 0.5	39.4 \pm 6.4	13.0 \pm 2.6	20.6 \pm 0.4
2-jet	15.1 \pm 0.3	56.1 \pm 11.7	10.8 \pm 3.6	21.6 \pm 2.1

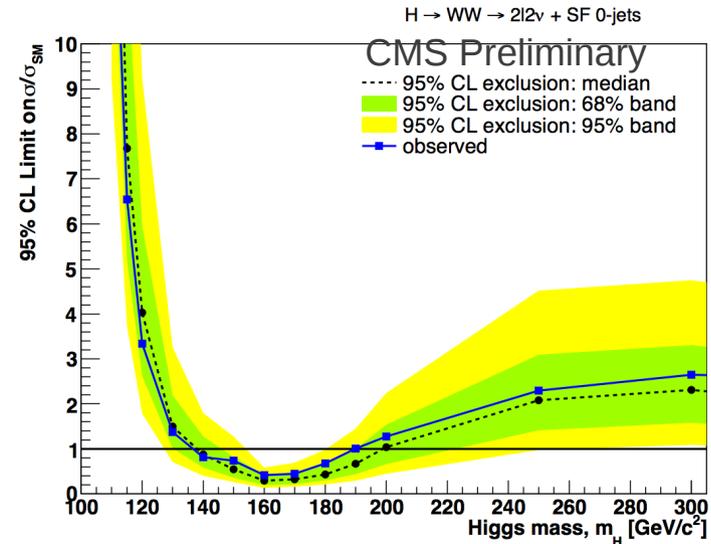


Individual Subchannels : Shape Analysis

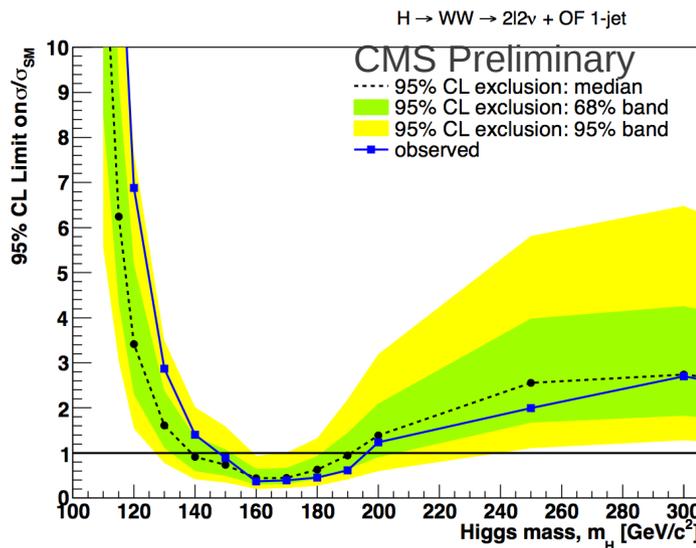
Opposite
Flavor
0-Jet



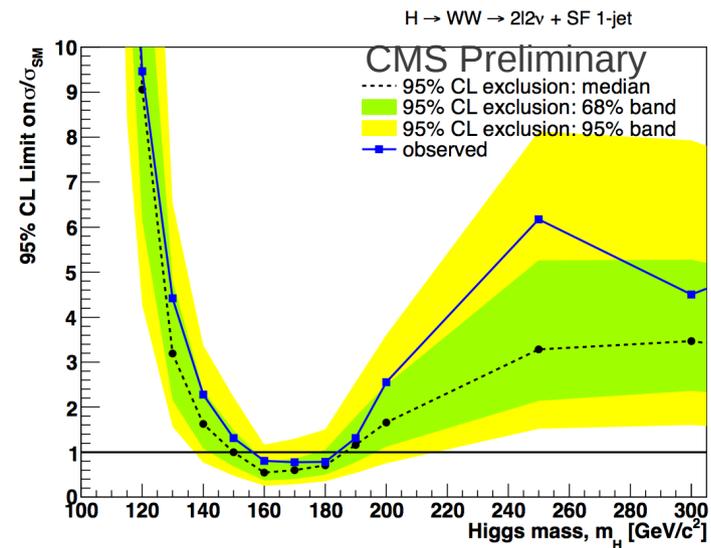
Same
Flavor
0-Jet



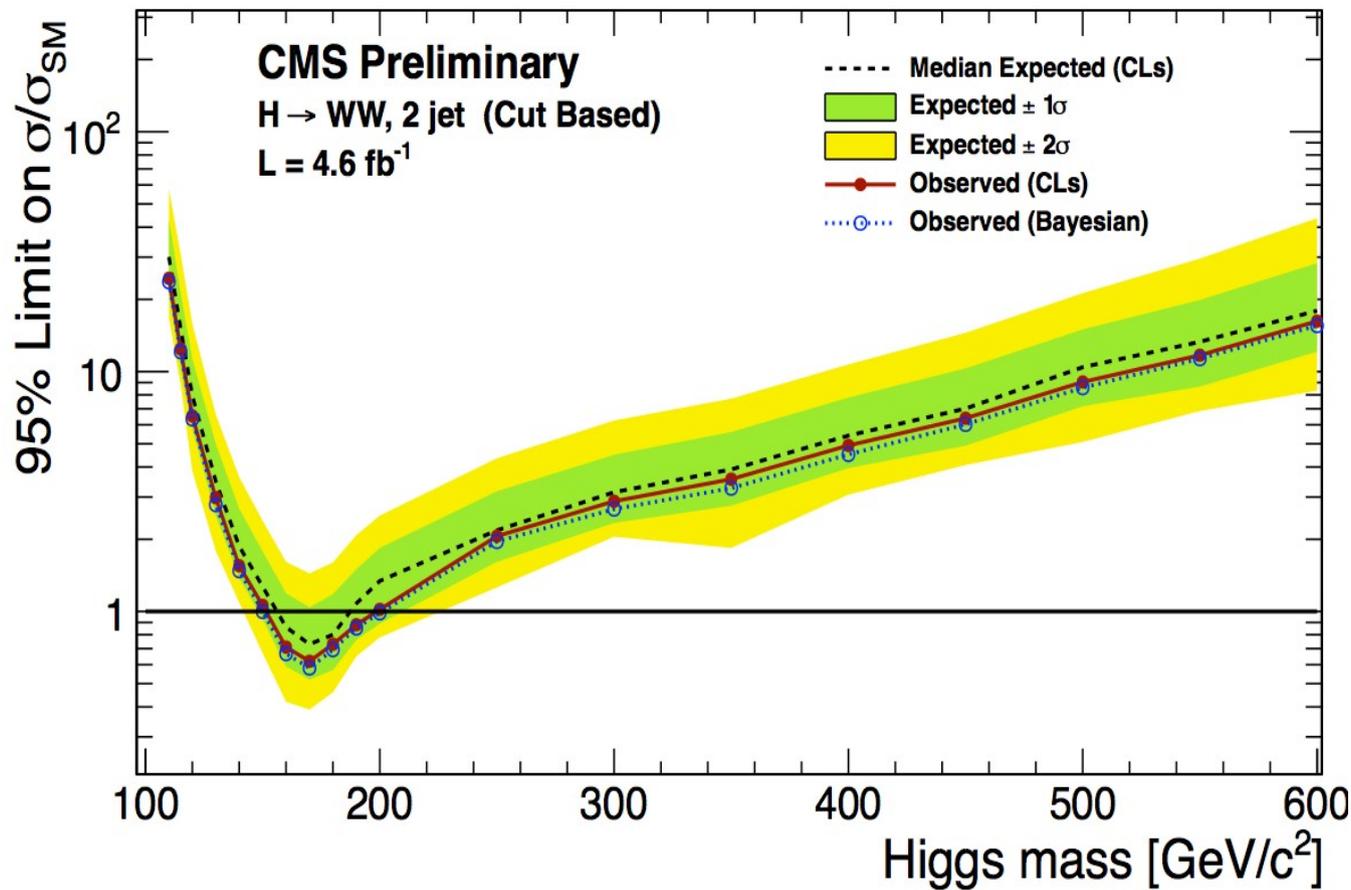
Opposite
Flavor
1-Jet



Same
Flavor
1-Jet



VBF Sub-channel



Fermiophobic Higgs Production

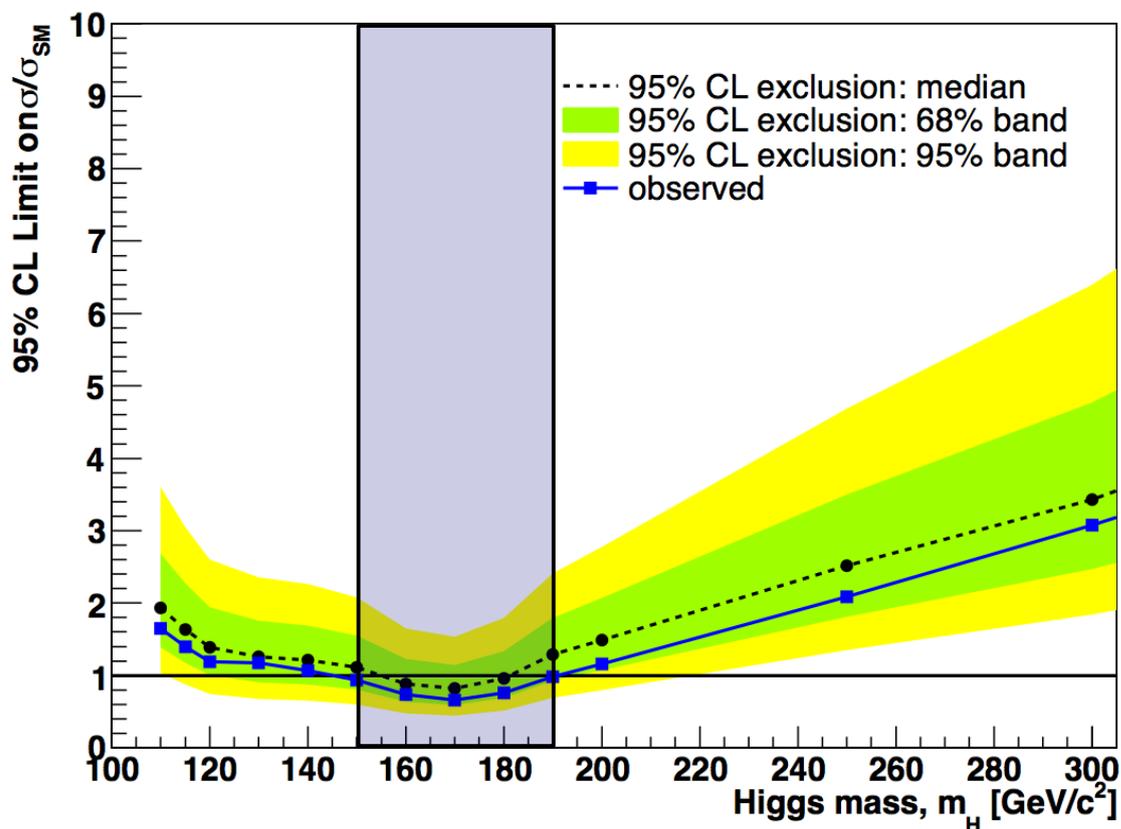
A Higgs boson without Yukawa couplings to fermions may be considered the most minimal scenario : “**Fermiophobic**”

- WW branching ratio enhanced
- No Gluon Fusion Production

Fermiophobic scenario excluded with masses in the range **[150 GeV, 190 GeV]**

CMS Preliminary

$H \rightarrow WW \rightarrow 2l2\nu + 0/1/2$ -jets, fermiophobic





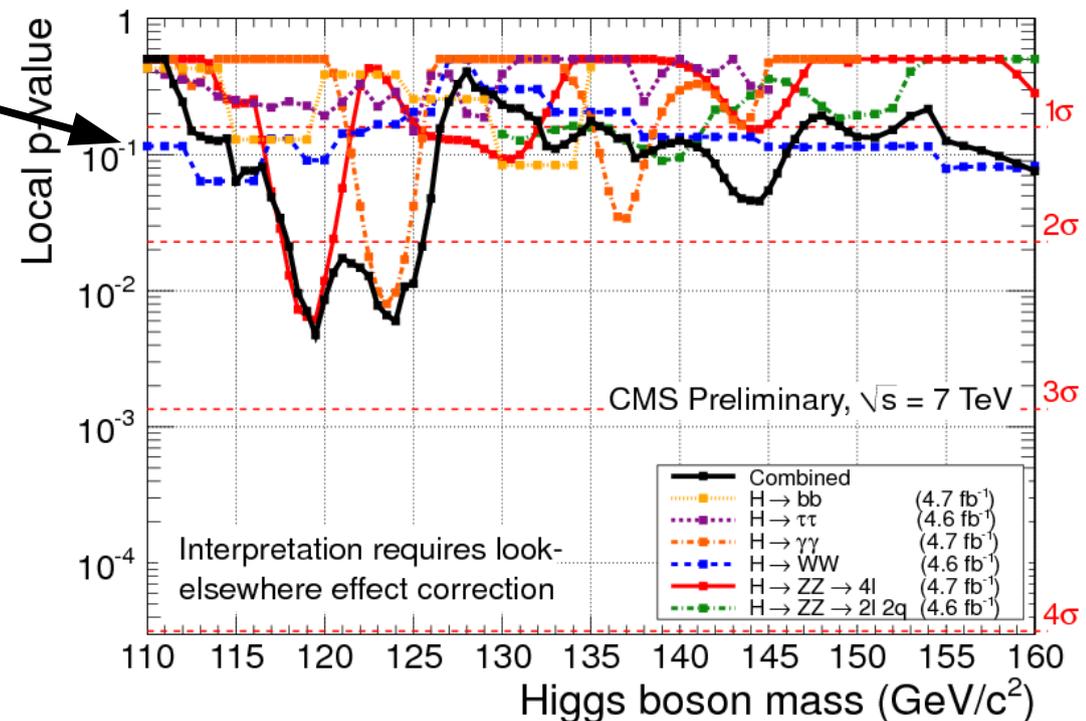
Observed Signal Significance

Quantified by the “p-value”:

Probability to observe a background-only fluctuation as significant or more significant as the current observation

H → WW in Blue

Results statistically **compatible** with the **background only** hypothesis **AND** the **signal+background** hypothesis



High Mass Higgs Width Systematic

Higgs Width Uncertainty @ High Mass

- $50\% * (m_H/1000 \text{ GeV})^3$

CLs-LHC Procedure : Limits

- Construct this test statistic:
$$\tilde{q}_\mu = -2 \ln \frac{\mathcal{L}(\text{data}|\mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})}$$
 “Profile Likelihood”

$\hat{\mu}, \hat{\theta} \rightarrow$ nuisance values maximizing L

$\hat{\theta}_\mu \rightarrow$ nuisance values maximizing L given signal strength μ

Note: to build the test statistic requires to perform a maximum likelihood fit to the observed data (and each toy) \rightarrow **“Profiling”**

q_μ^{obs} : observed value of the test statistic

θ_μ^{obs} and θ_0^{obs} : best fit nuisance values for signal only & signal+bkg hypotheses

- Generate Toys to construct PDFs : $f(\tilde{q}_\mu|\mu, \hat{\theta}_\mu^{\text{obs}})$ $f(\tilde{q}_\mu|0, \hat{\theta}_0^{\text{obs}})$
- Evaluate p-values:
$$p_\mu = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{\text{obs}} | \text{signal+background}) = \int_{\tilde{q}_\mu^{\text{obs}}}^{\infty} f(\tilde{q}_\mu|\mu, \hat{\theta}_\mu^{\text{obs}}) d\tilde{q}_\mu$$

$$1 - p_b = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{\text{obs}} | \text{background-only}) = \int_{q_0^{\text{obs}}}^{\infty} f(\tilde{q}_\mu|0, \hat{\theta}_0^{\text{obs}}) d\tilde{q}_\mu$$
- Define CLs :
$$CL_s(\mu) = \frac{p_\mu}{1 - p_b}$$
- For 95% CL upper limit, find μ for which $CL_s(\mu) = 0.05$

CLs-LHC Procedure :

Quantify an Excess

- Use test statistic with $\mu=0$:
$$q_0 = -2 \ln \frac{\mathcal{L}(\text{data}|0, \hat{\theta}_0)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta})}$$
- Generate Toys to construct PDF : $f(q_0|0, \hat{\theta}_0^{\text{obs}})$
- Evaluate p-value:
$$p_0 = P(q_0 \geq q_0^{\text{obs}}) = \int_{q_0^{\text{obs}}}^{\infty} f(q_0|0, \hat{\theta}_0^{\text{obs}}) dq_0.$$
- Convert to Significance :
$$p = \int_Z^{\infty} \frac{1}{\sqrt{2\pi}} \exp(-x^2/2) dx$$

5σ significance \rightarrow pvalue = 2.8×10^{-7}

Likelihood Function

$$\mathcal{L}(\text{data} | \mu, \theta) = \text{Poisson}(\text{data} | \mu \cdot s(\theta) + b(\theta)) \cdot p(\tilde{\theta} | \theta).$$



Parameterization of the Systematic Errors

$$\text{Poisson}(\text{data} | \mu s + b) = \prod_i \frac{(\mu s_i + b_i)^{n_i}}{n_i!} e^{-\mu s_i - b_i}$$